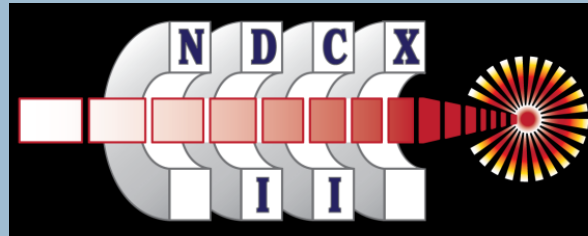# The NDCX-II accelerator facility for Heavy Ion Fusion Science[*]

A. Friedman, J. J. Barnard, R. H. Cohen, M. Dorf, D. P. Grote,
S. M. Lund, W. M. Sharp, *LLNL*

D. Arbelaez, A. Faltens, J. Galvin, W. Greenway, E. Henestroza, J.-Y. Jung,
J. W. Kwan, E. P. Lee, B. G. Logan, L. L. Reginaro, P. K. Roy, P. A. Seidl,
J. H. Takakuwa, J.-L. Vay, W. L. Waldron, *LBNL*

R. C. Davidson, E. P. Gilson, I. D. Kaganovich, *PPPL*

Paper G07.01, 53nd Annual Meeting of the APS Division of Plasma Physics
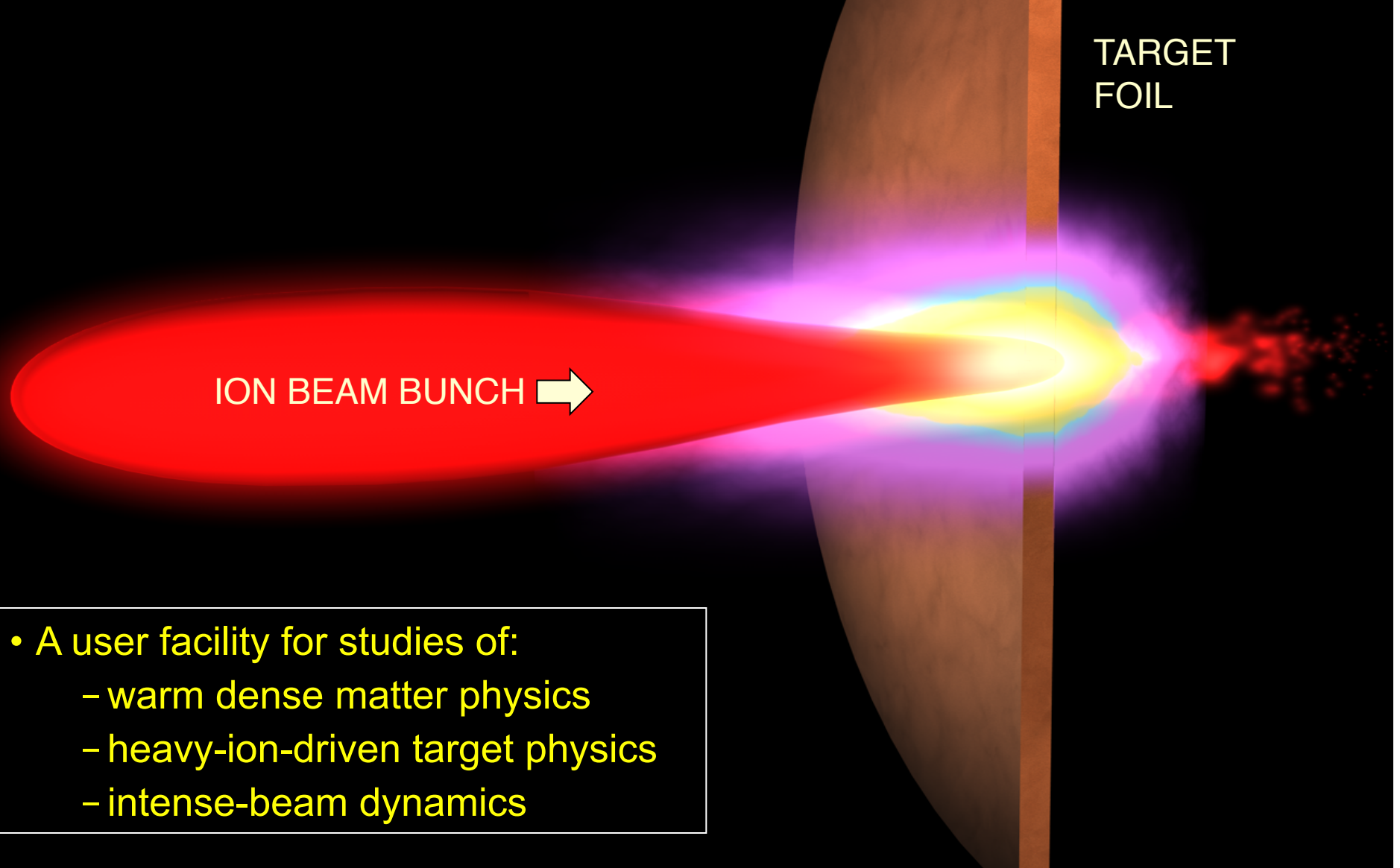*Salt Lake City, November 15, 2011*

The Heavy Ion Fusion Science
Virtual National Laboratory

Neutralized Drift Compression Experiment-II (NDCX-II)

TARGET FOIL

ION BEAM BUNCH ⟹

- A user facility for studies of:
    - warm dense matter physics
    - heavy-ion-driven target physics
    - intense-beam dynamics

The drift compression process is used to shorten an ion bunch

- Induction cells impart a head-to-tail velocity gradient ("tilt") to the beam
- The beam shortens as it "drifts" down the beam line

- In non-neutral drift compression, the space charge force opposes ("stagnates") the inward flow, leading to a nearly mono-energetic compressed pulse:
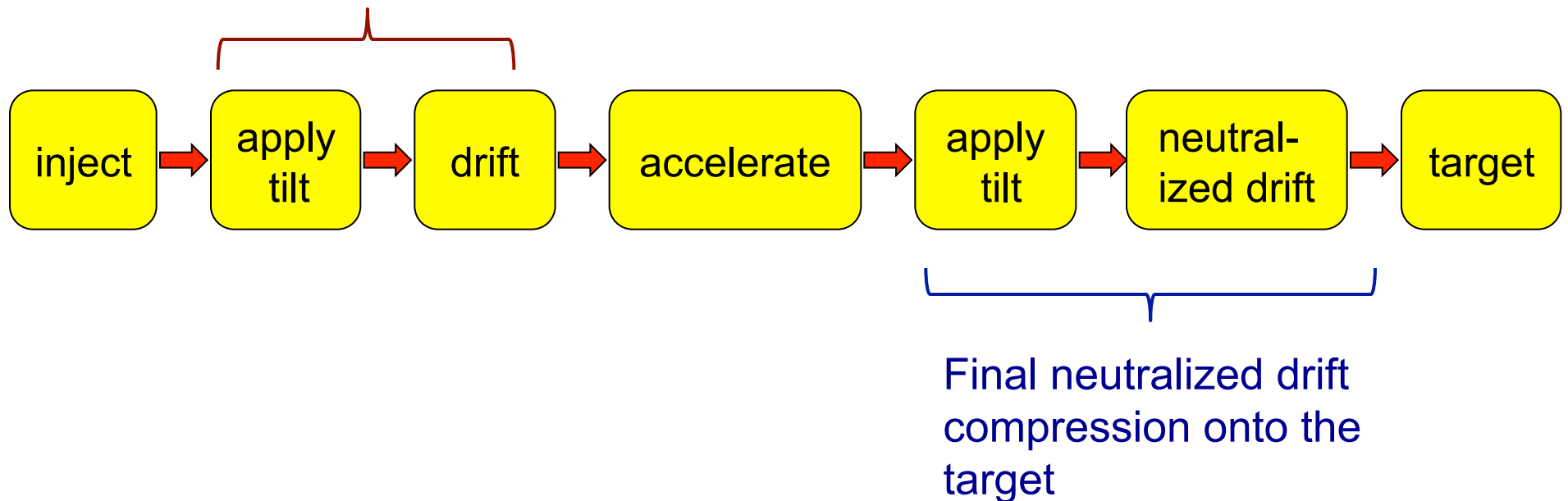
(in beam frame)
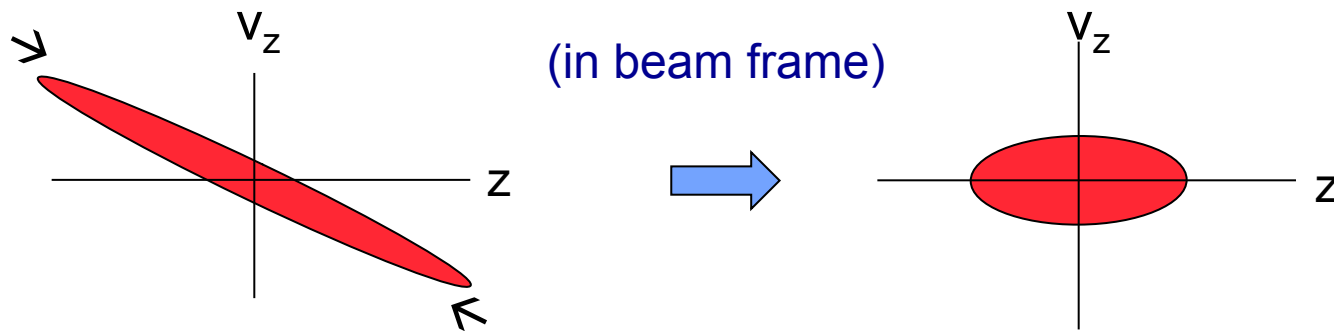
- In neutralized drift compression, the space charge force is eliminated, resulting in a shorter pulse but a larger velocity spread:
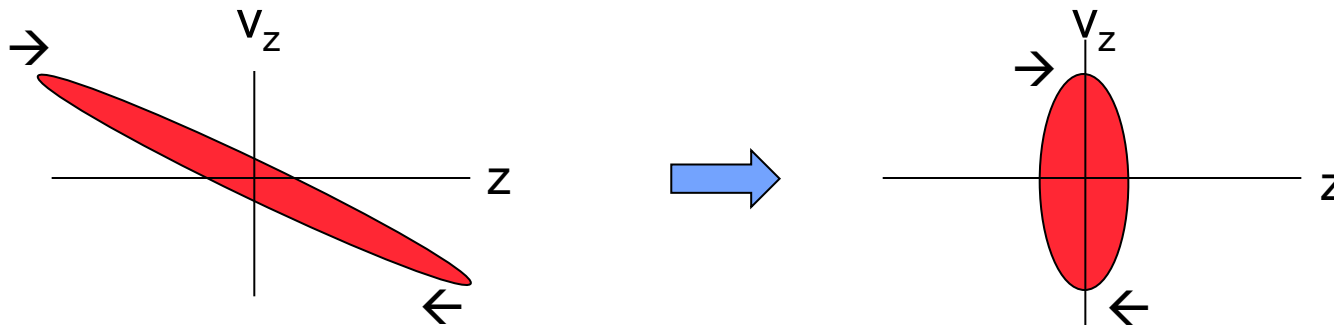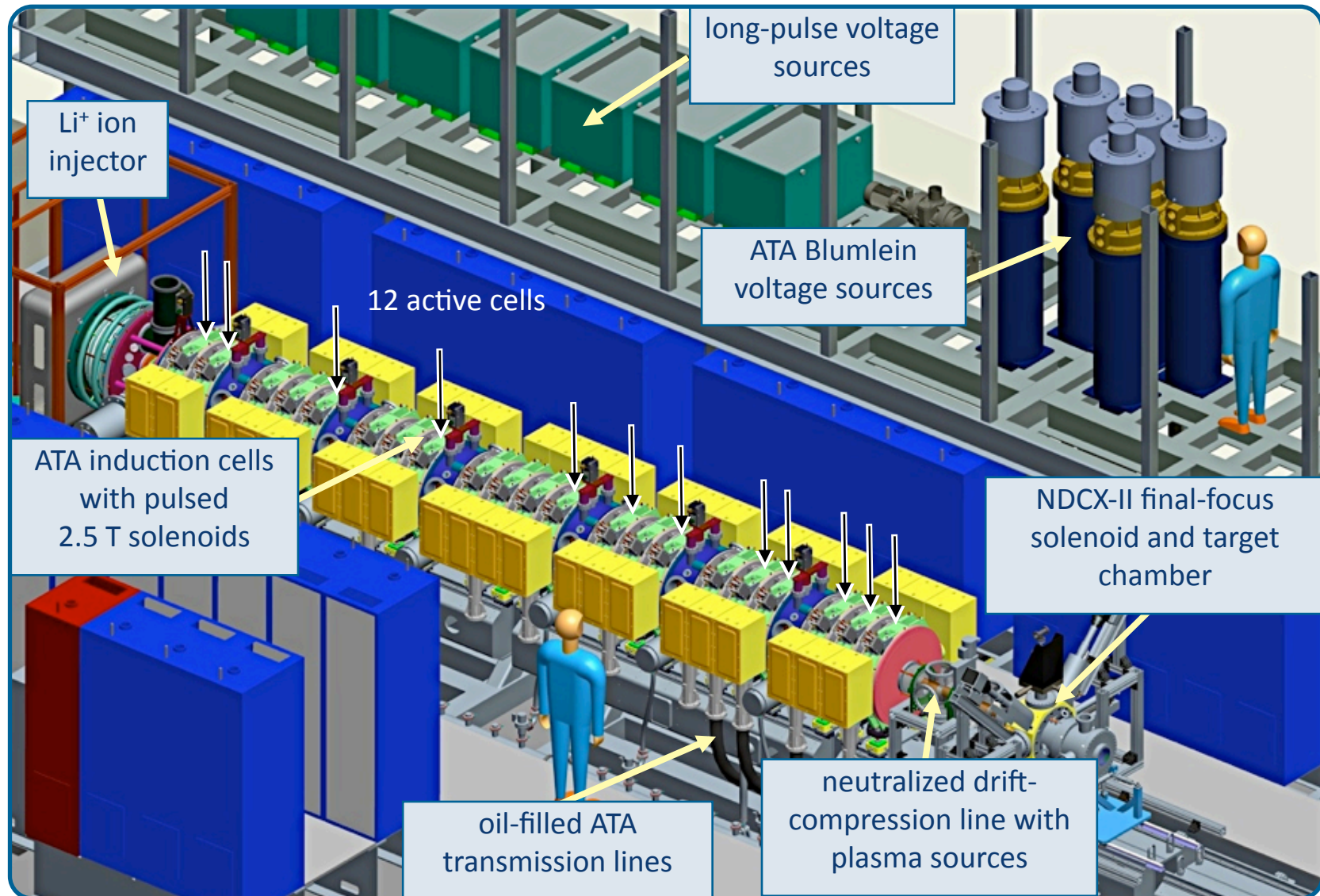
Drift compression is used twice in NDCX-II

Initial non-neutral pre-bunching for
early use of 70-ns 250-kV Blumlein
power supplies from ATA

| inject | → | apply tilt | → | drift | → | accelerate | → | apply tilt | → | neutral-ized drift | → | target |

Final neutralized drift
compression onto the
target

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12-cell NDCX-II baseline layout

long-pulse voltage sources

Li+ ion injector

ATA Blumlein voltage sources

12 active cells

ATA induction cells with pulsed 2.5 T solenoids

NDCX-II final-focus solenoid and target chamber

oil-filled ATA transmission lines

neutralized drift-compression line with plasma sources

Accelerating waveforms are either long-pulse moderate-voltage or short-pulse high-voltage (Blumleins)

250 kV "flat-top" measured waveform from test stand
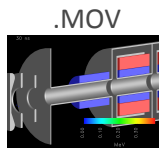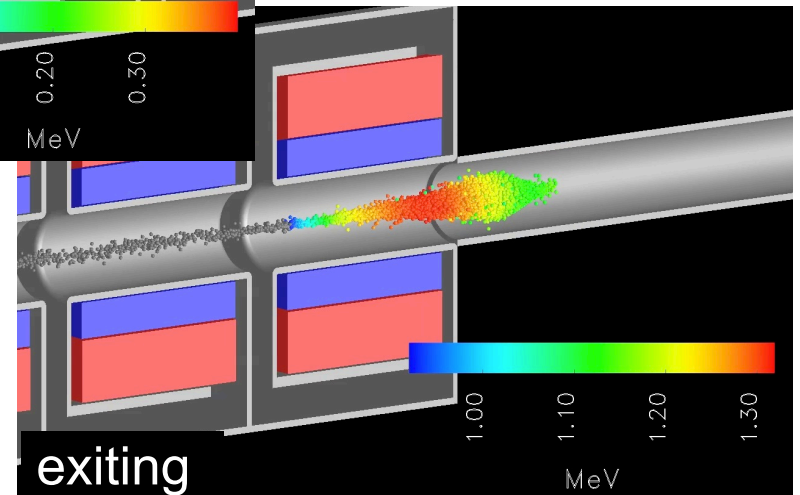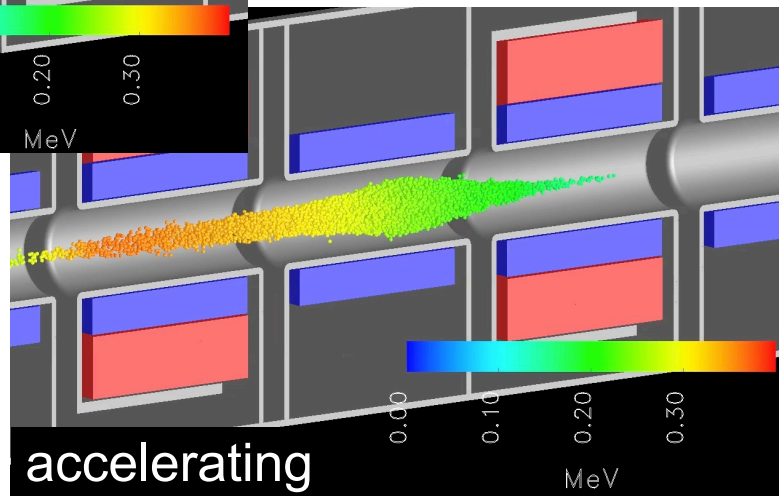
200 kV "ramp" measured waveform from test stand

"shaped" for initial bunch compression (scaled from measured waveforms)

"shaped" to equalize beam energy after injection

40g.002-12

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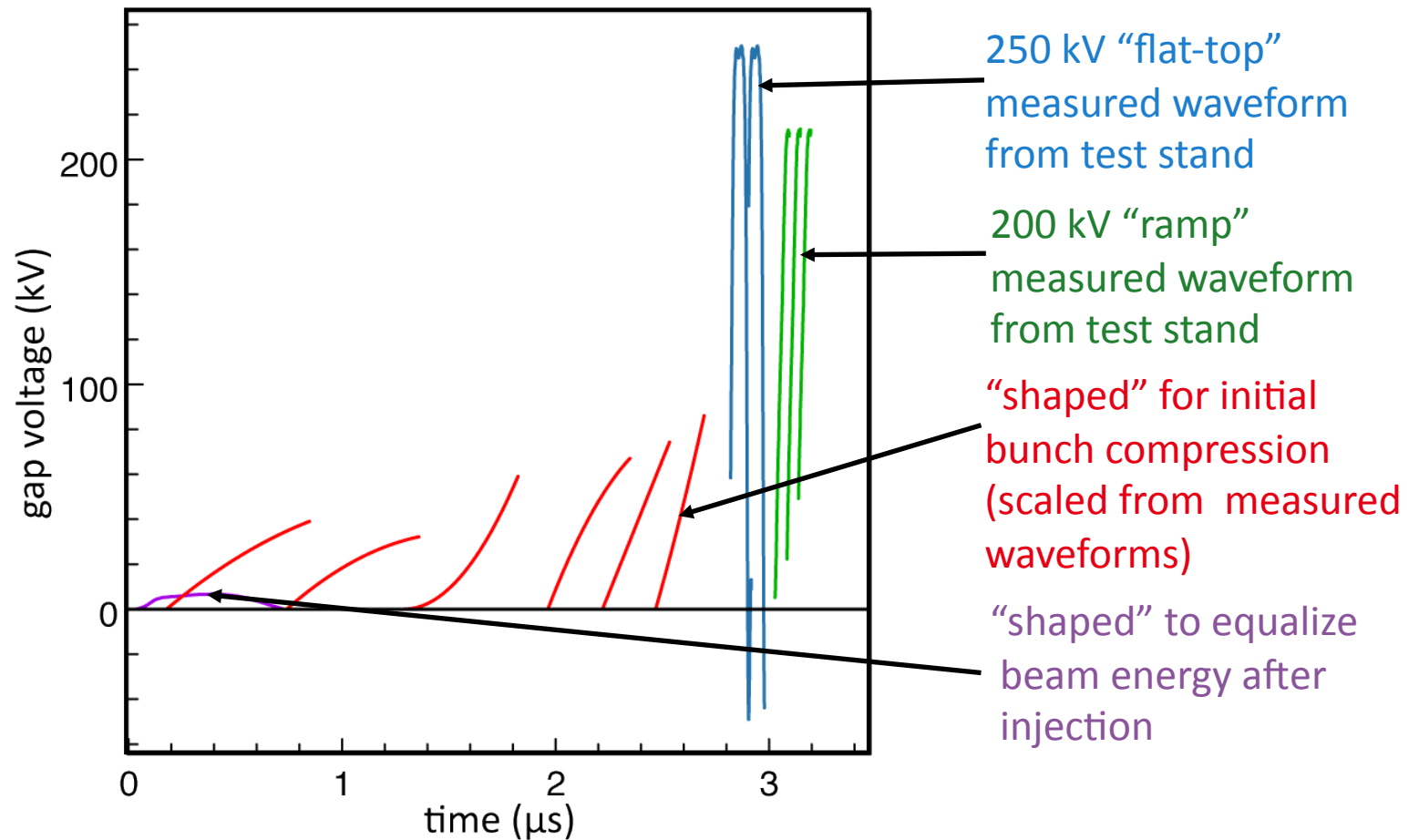
3-D Warp simulation with perfectly aligned solenoids (close-up)

entering

accelerating

exiting

.MOV
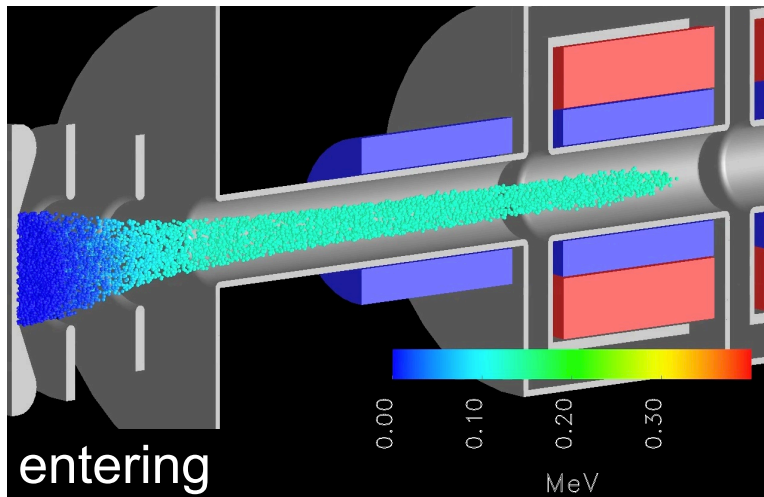
ndcx49c2_016_1280res_zoom.mov

.WMV
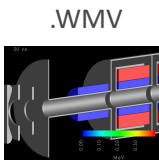
ndcx49c2_016_1280res_zoom.wmv
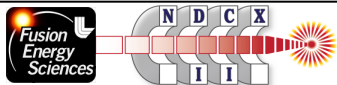
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LBNL B58 on 11/9/11, showing injector and initial induction cells

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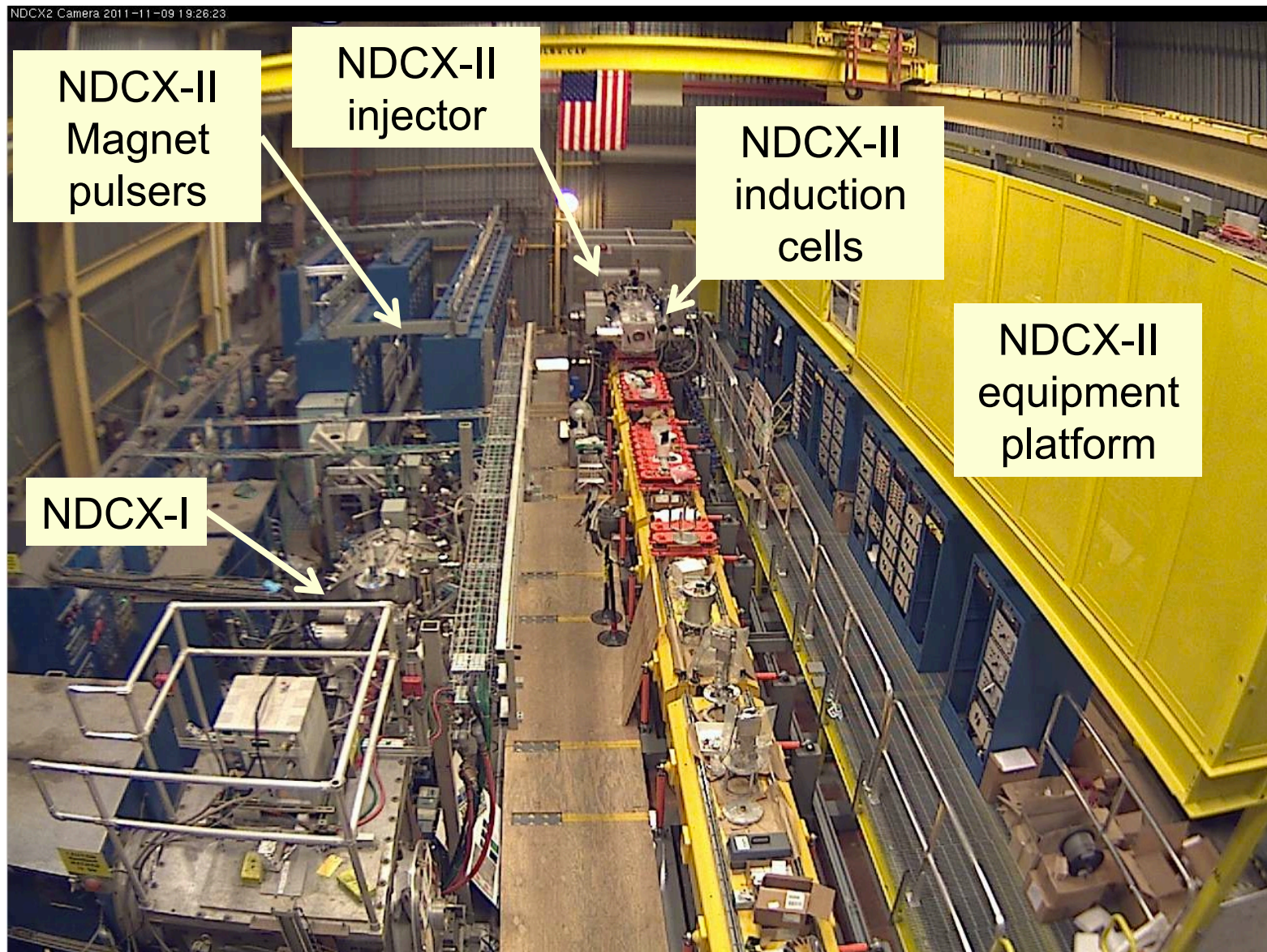
Construction of NDCX-II began July, 2009, with $11M of ARRA funds and many ATA parts

Acceptance-test configuration (Nov. 2011)

Configuration at end of ARRA funding (Dec. 2011)
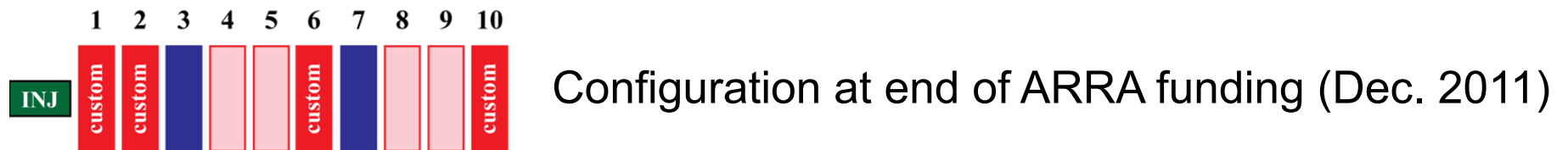
We plan to spend an additional ~$500 k to achieve a 27-lattice-period, 12-active cell, 1.2 MeV configuration by the end of March, 2012:

Active Induction Cell — A

Inactive Induction Cell — I

Diagnostics Cell — D
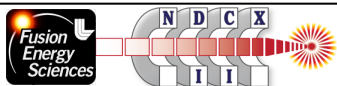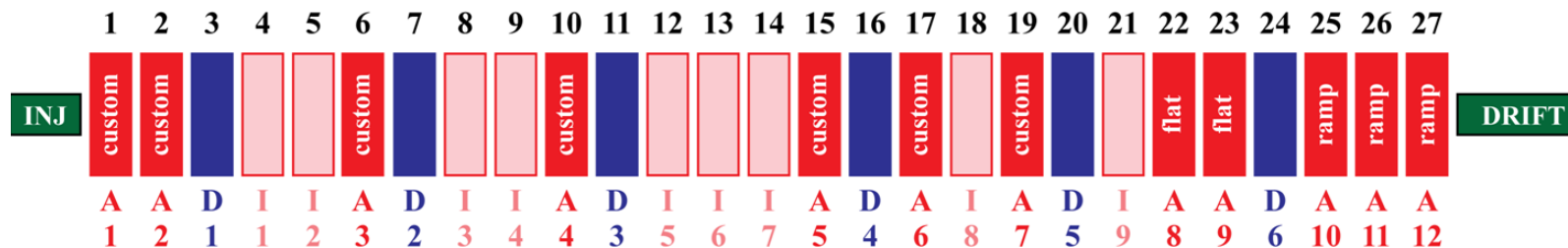
We expect a steady increase in beam parameters as the machine and our experience mature

September 2011 HEDLP call for proposals required the HIFS-VNL to provide a timeline of estimated performance for early users of the facility:

Li+, 12 active cells, 1.2 MeV final ion energy 600 ns initial pulse duration			
Date	I_{source}	τ_{target}	r_{target}	F_{target}
	Source current (mA)	Pulse duration at target (ns) biparabolic equivalent full width	Beam radius at target (mm) containing 50% of the beam current	Fluence (J/cm^2) avg'd. over r_{target} and within τ_{target}
March, 2012	30	4	3	0.1
June, 2012	60	3.5	2	0.3
Sept, 2012	90	2.5	1.5	0.9
Dec, 2012	90	1.5	1	2.1
Sept, 2013	90	0.85	0.55	6.8

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Target chamber will resemble those of Titan/Trident/LCLS MECI; funding to procure the chamber shell has been approved
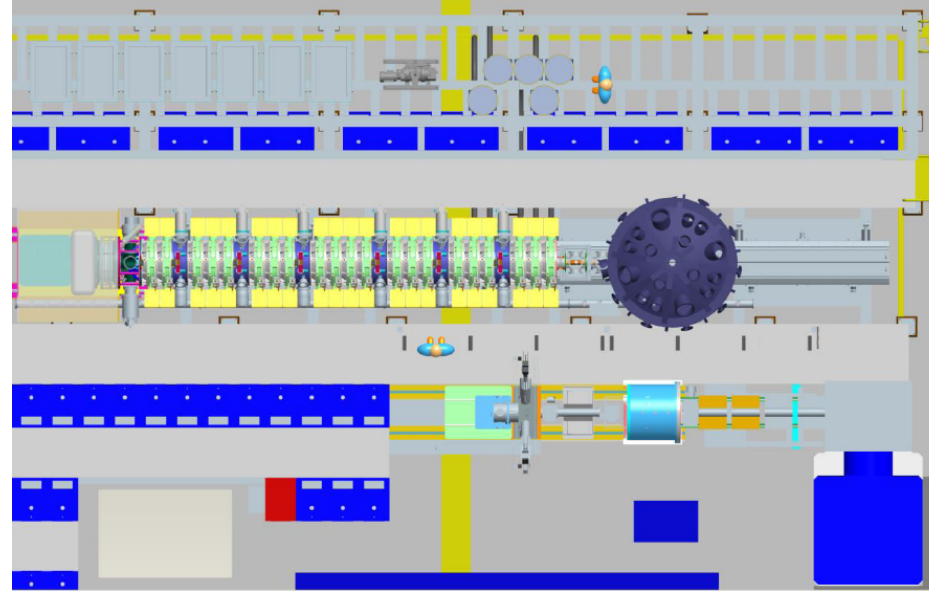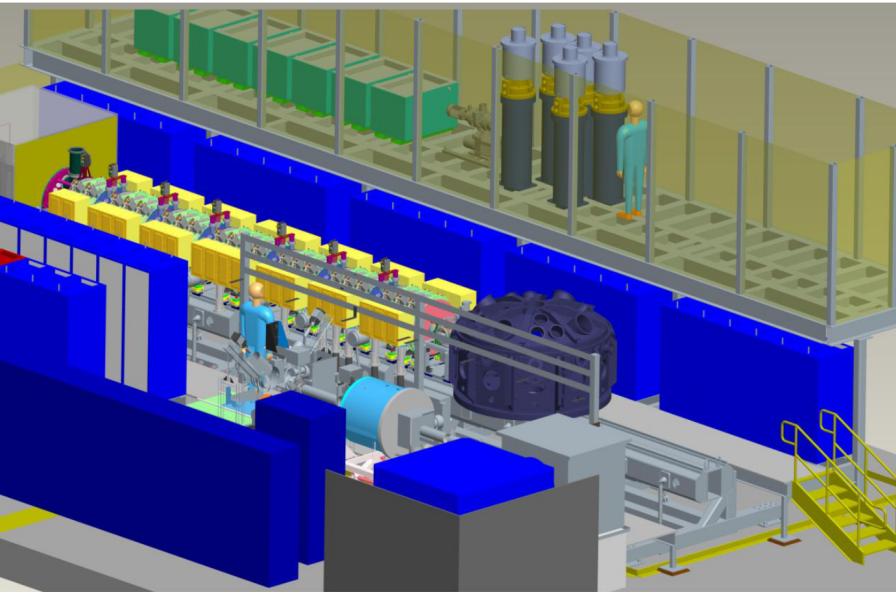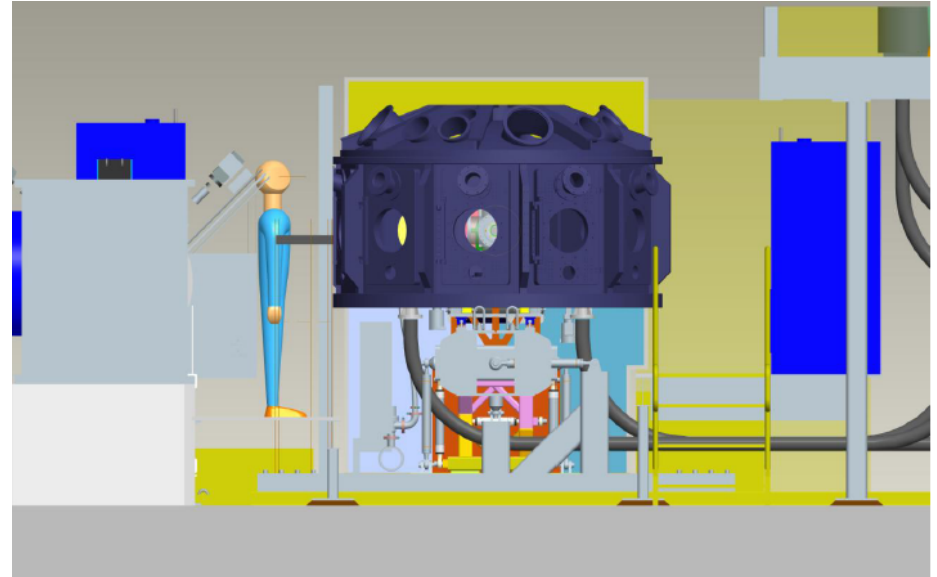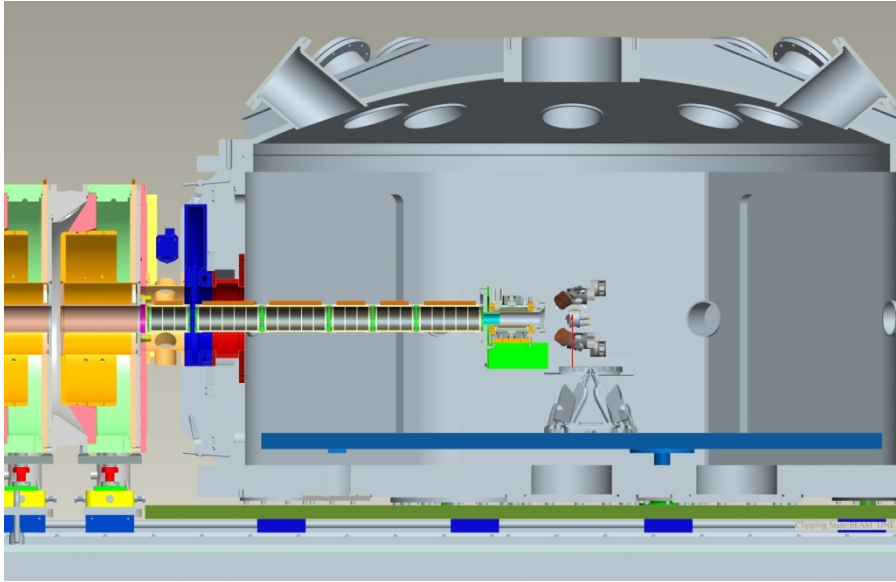
NDCX-II can be extended to 3.1 MeV straightforwardly

- 27 periods (12 active cells) baseline offers 1.2 MeV

- 37 periods can yield 3.1 Mev (!)

- We need only append 10 lattice periods

  – 9 active Blumlein-powered cells:

    6 more 250 kV "flat-top" (total of 8)

    3 more final 0-200 kV "ramps" (total of 6)

  – 1 diagnostic / pumping cell

- Incremental cost of ~ $1.5 M

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NDCX-II performance for typical cases in 12-21 cell configurations

	NDCX-I (bunched beam)	NDCX-II 12-cell	NDCX-II 21-cell
Ion species	K$^+$ (A=39)	Li$^+$ (A=7)	Li$^+$ (A=7)
Charge	15 nC	50 nC total 25 2xFWHM	50 nC total 30 2xFWHM
Ion kinetic energy	0.3 MeV	1.2 MeV	3.1 MeV
Focal radius (50% of beam)	2 mm	0.6 mm	0.7 mm
Duration (bi-parabolic measure = √2 FWHM)	2.8 ns	0.9 ns	0.4 ns
Peak current	3 A	36 A	86 A
Peak fluence (time integrated)	0.03 J/cm^2	13 J/cm^2	22 J/cm^2
Fluence w/in 0.1 mm diameter, w/in duration		8 J/cm^2	17 J/cm^2
Max. central pressure in Al target		0.07 Mbar	0.23 Mbar
Max. central pressure in Au target		0.18 Mbar	0.64 Mbar

NDCX-II estimates are from (r,z) Warp runs (no misalignments), and assume uniform 1 mA/cm^2 emission, high-fidelity acceleration pulses and solenoid excitation, perfect neutralization in the drift line, and an 8-T final-focus solenoid; they also employ no fine energy correction (e.g., tuning the final tilt waveforms)

NDCX-II will be a unique user facility for warm dense matter, IFE target physics, and intense-beam physics.
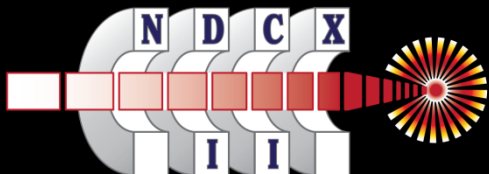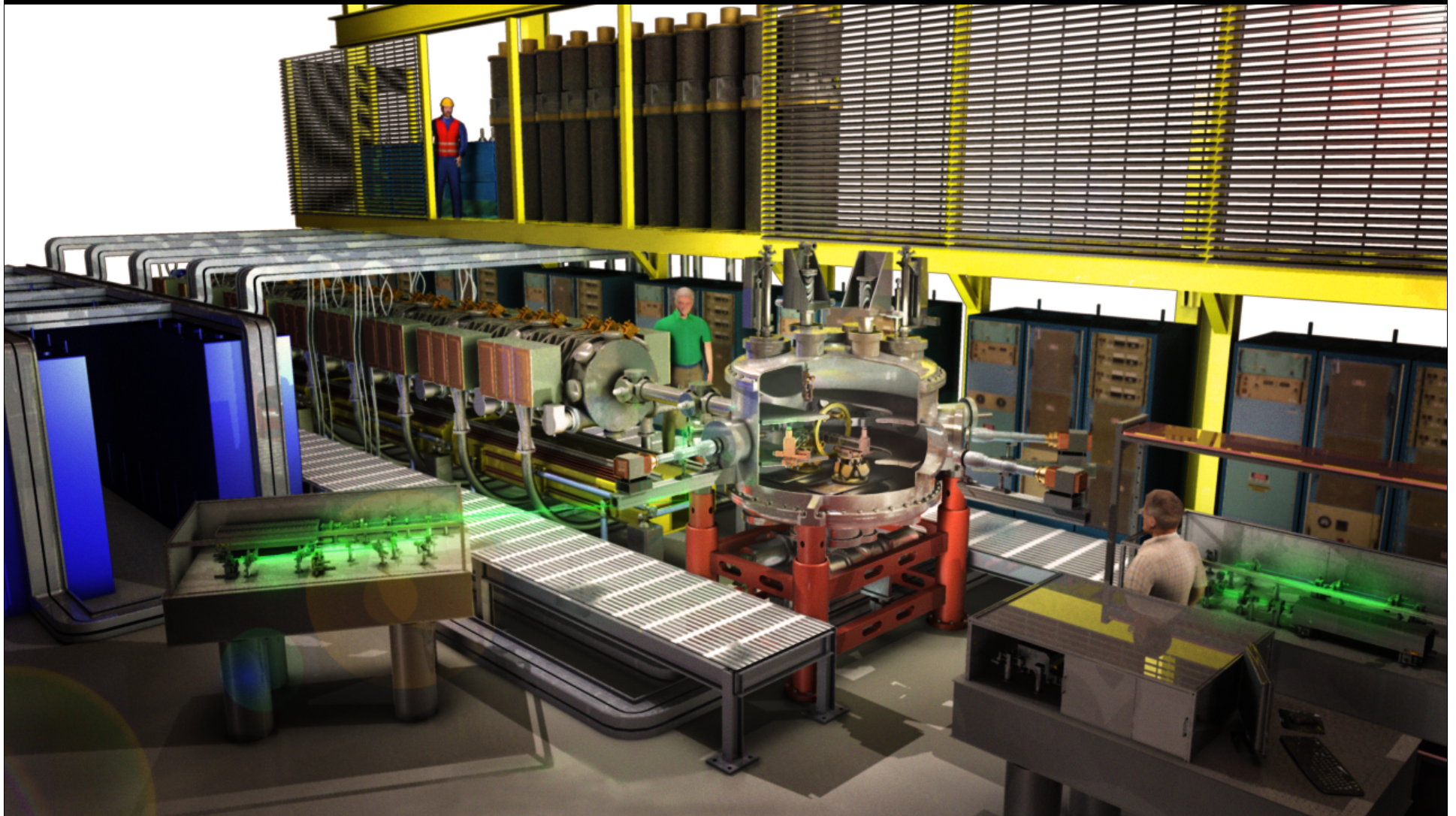
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This session, talks 2-7

G07.2: Prabir Roy, NDCX-II injector with a 10.9 cm diameter Li$^+$ ion source

G07.3: Joe Kwan, Completion of NDCX-II facility and initial tests

G07.4: Peter Seidl, Beam Phase Space of an intense ion beam in a neutralizing plasma

G07.5: Igor Kaganovich, Review of methods for neutralization of intense high-energy ion beam pulses by electrons

G07.6: Jean-Luc Vay, Novel Simulation Methods in the Particle-In-Cell Framework Warp

G07.7: A. Andronov, Secondary electron emission in the limit of low energy and its effect on high energy physics accelerators

Today at 4:24 in Ballroom I:

JO8.13: Matt Terry, Directly driven, tamped heavy ion ICF targets

Wednesday at 3:30 in Ballroom AC:

PI3.4 : Mikhail Dorf, Enhanced collective focusing of intense neutralized ion beam pulses in the presence of weak solenoidal magnetic fields

Wednesday PM posters in Session PP9, nos. 78, 81, 82:

PP9.78: Albert Yuen, Rarefaction Waves in Van der Waals Fluids

PP9.81: John Barnard, Modeling of EOS and Ion Coupling Experiments on NDCX-II*

PP9.82: Wangyi (Bobby) Liu, Modeling droplet breakup effects with diffuse interface methods in ALE-AMR code with application in modeling NDCX-II experiments

Friday posters in session YP9, nos. 17 - 25:

YP9.17: Bill Sharp, Alternate operating scenarios for NDCX-II

YP9.18: Dave Grote, Characterization of the NDCX-II accelerator via simulation

YP9.19: Gilles Maynard, Multiple scattering of slow Ions in a partially degenerate electron fluid

YP9.20: Sagar Vijay, Prompt gas desorption due to ion impact on accelerator structures

YP9.21: Nikolas Logan, Thermodynamic bounds on nonlinear electrostatic fluctuations in intense charged particle beams

YP9.22: Edward Startsev, Nonlinear effects of beam-plasma instabilities on neutralized propagation of intense ion beams in background plasma

YP9.23: Hua Wang, Direct and beat-wave excitation of collective beam modes in the Paul Trap Simulator Experiment

YP9.24: A. Stepanov, Beam-plasma interaction experiments on the Princeton Advanced Test Stand

YP9.25: E. Gilson, Collective mode excitation by asymmetric fields in alinear Paul trap to study beam stability

Abstract

The NDCX-II accelerator facility for Heavy Ion Fusion Science[*]

A. FRIEDMAN, J. J. BARNARD, R. H. COHEN, M. DORF, D. P. GROTE, S. M. LUND, W. M. SHARP, *LLNL*; D. ARBELAEZ, A. FALTENS, J. GALVIN, W. GREENWAY, E. HENESTROZA, J.-Y. JUNG, J. W. KWAN, E. P. LEE, B. G. LOGAN, L. L. REGINATO, P. K. ROY, P. A. SEIDL, J. TAKAKUWA, J.-L. VAY, W. L. WALDRON, *LBNL*; R. C. DAVIDSON, E. P. GILSON, I. D. KAGANOVICH, *PPPL*---

The Neutralized Drift Compression Experiment-II (NDCX-II) will generate ion beams for studies of Warm Dense Matter, target physics for heavy-ion-driven Inertial Fusion Energy, and intense-beam dynamics. NDCX-II will accelerate a 20-50 nC Li pulse to 1.2-3 MeV, compress it to sub-ns duration in a neutralizing plasma, and focus it onto a target. Construction of the induction accelerator and compression line at LBNL is approaching completion. We briefly describe the NDCX-II "physics design" [A. Friedman, *et al.*, *Phys. Plasmas* **17**, 056704 (2010)], the simulation studies that enabled it, variations (e.g., for other ions), plans for commissioning over the next year, and some possible experiments using the machine itself and extensions.

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3-D Warp simulation with perfectly aligned solenoids

entering

accelerating

exiting

.MOV
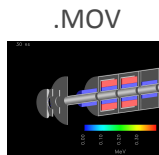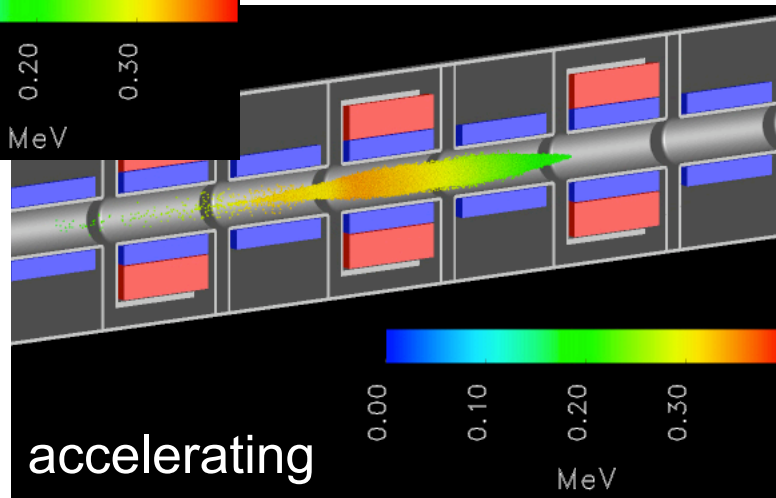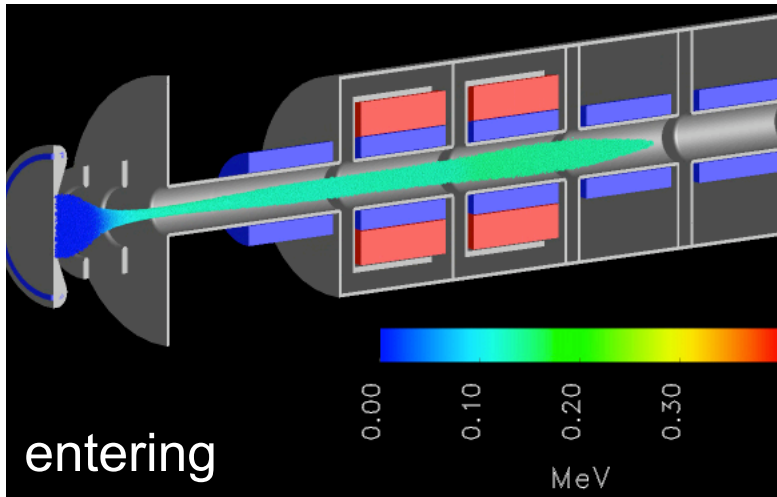
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.WMV
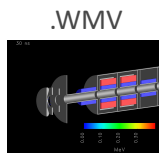
ndcx49c2_016_1280res.wmv

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Additional Material

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The baseline hardware configuration is as presented during the April 2010 DOE Project Review
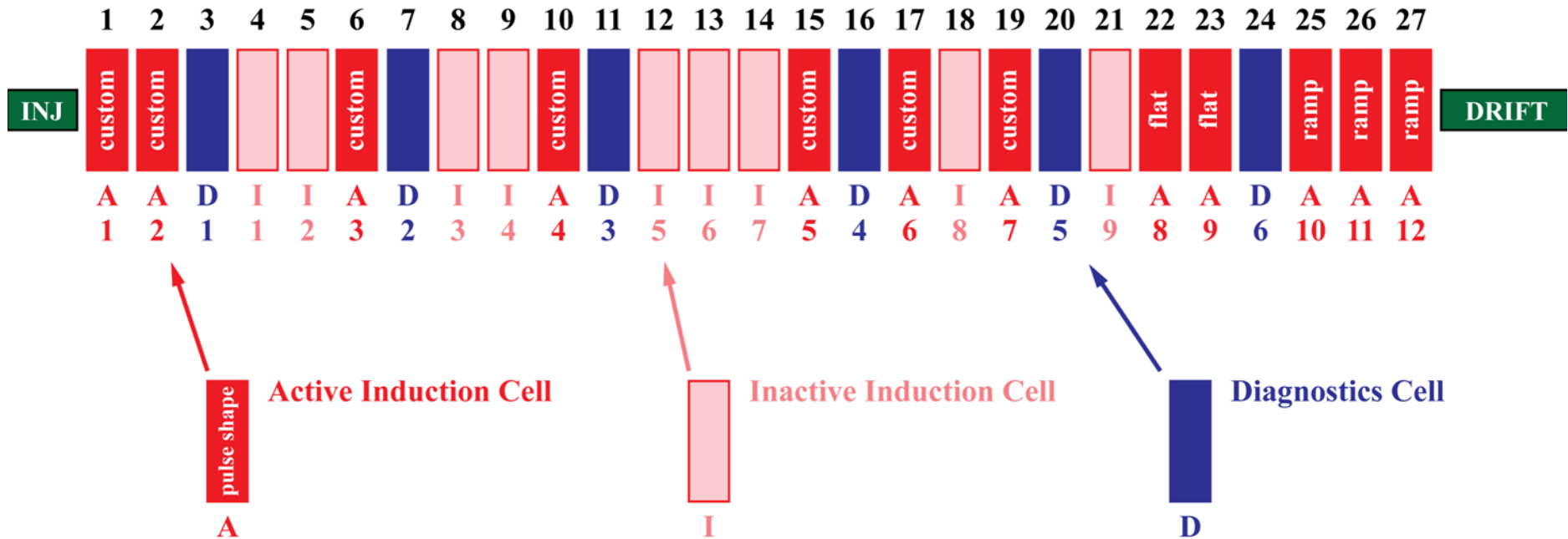
- 27 lattice periods after the injector
- 12 active induction cells
- Beam charge ~50 nano-Coulombs
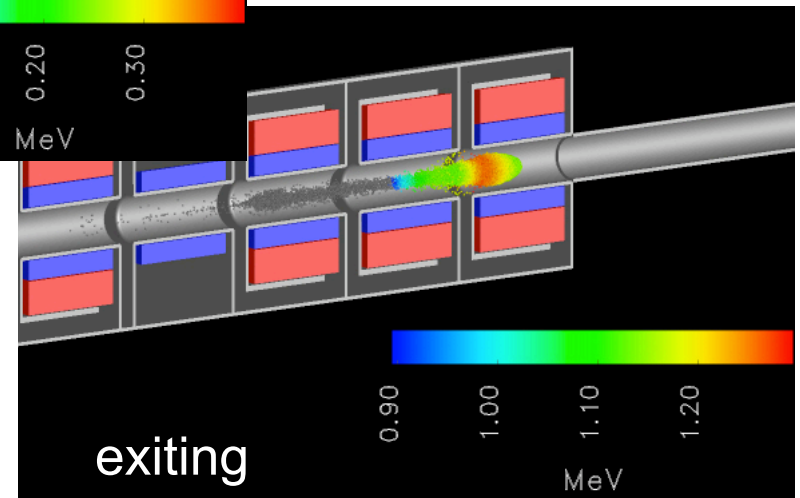- FWHM < 1 ns
- Kinetic energy ~ 1.2 MeV

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12-cell NDCX-II baseline layout

long-pulse voltage sources

Li⁺ ion injector

9 inactive cells

ATA Blumlein voltage sources

ATA induction cells with pulsed 2.5 T solenoids

NDCX-II final-focus solenoid and target chamber

oil-filled ATA transmission lines

neutralized drift-compression line with plasma sources

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12-cell NDCX-II baseline layout

long-pulse voltage sources
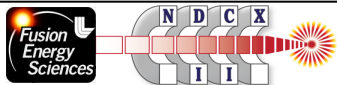
Li+ ion injector

6 diagnostic cells

ATA Blumlein voltage sources

ATA induction cells with pulsed 2.5 T solenoids

NDCX-II final-focus solenoid and target chamber

oil-filled ATA transmission lines

neutralized drift-compression line with plasma sources

Development of the physics design

Space-charge-dominated ion beams are non-neutral plasmas

- For a beam in an accelerator to be near equilibrium, it must be in (time-averaged) transverse force balance.
  - Usually, the beam's thermal pressure ("emittance") and the applied confining forces are the large terms, with space charge a perturbation.
  - In our beams, the primary balance is between space-charge repulsion and the confining forces; thermal pressure is modest, flow is quasi-laminar.
- "Generalized perveance" is space charge potential energy / beam k.e.:

$$K = \frac{2q\lambda}{4\pi\varepsilon_0 mv^2}$$

  - Almost all beams have modest K; e.g., the GSI RFQ has K ~ 4×10^{-6}.
  - Our beams usually have K's of 10^{-4} - 10^{-3}.
  - NDCX-II has a peak K of 10^{-2}; we must confine it steadily with solenoids

---

- These beams are collisionless ("long memory"), & exhibit collective behaviors
- They must be simulated, and analyzed, using the techniques of plasma physics (*e.g.*, particle-in-cell simulations, Vlasov equation).

ASP ("Acceleration Schedule Program") is a fast, purpose-built, 1-D PIC code for developing NDCX-II acceleration schedules

- Follows (z, v_z) phase space using a few hundred particles ("slices")

"Snapshots" of
line charge density $\lambda(z)$
and longitudinal beam
phase space $v_z(z)$,
550 ns into a
simulated shot:

it = 550, t = 550 ns
asp.py 2011–10–07 15:38:05 Rev 127
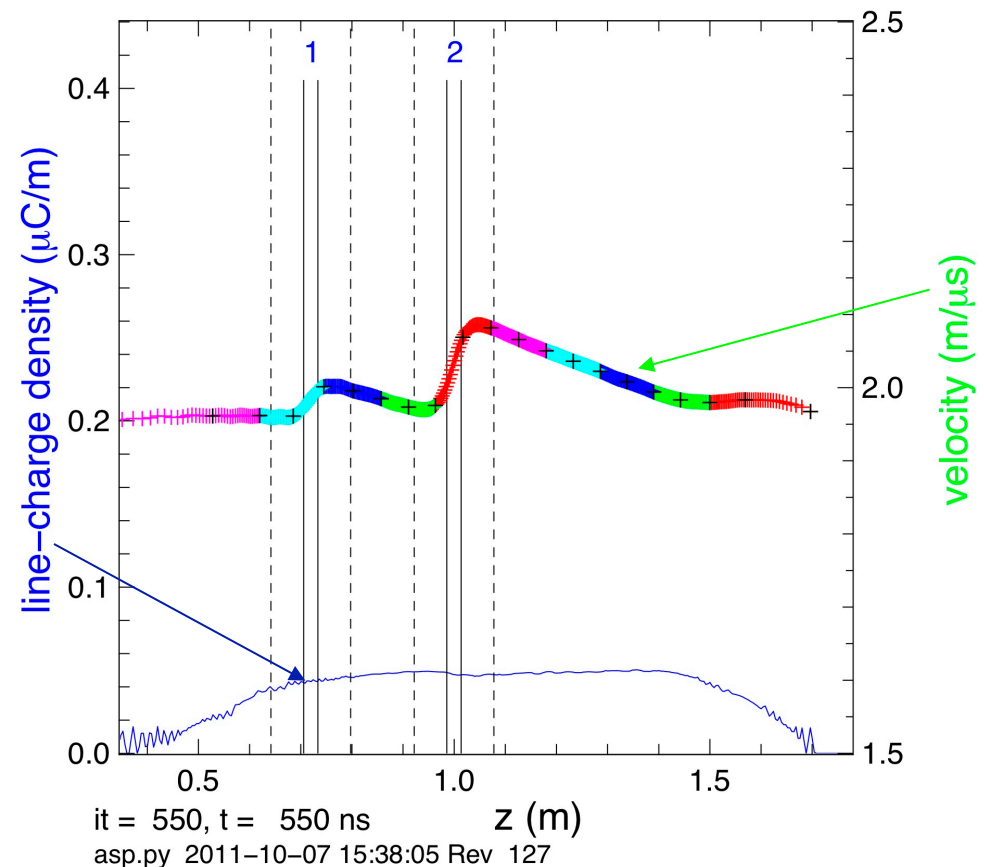
- Centroid tracking, to study imperfect alignment & beam steering via dipoles
- Optimization loops. for waveforms & timings, dipole strengths
- Interactive (Python language with Fortran for intensive parts)

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Warp is our full-physics beam simulation code, used for many applications; it too plays a critical role in the NDCX-II effort

- 1, 2, and 3-D electrostatic and electromagnetic field solvers

- first-principles and approximate models of accelerator "lattice" components

- space-charge-limited and current-limited injection models

- cut-cell boundaries for internal conductors in ES solver

- Adaptive Mesh Refinement (AMR)

- large Δt algorithms (implicit electrostatic, large $\omega_c\Delta t$)

- emission, ionization, secondaries, Coulomb collisions...

- parallel processing

- user-programmable via Python


```
0.00    0.10    0.20    0.30
              MeV
```
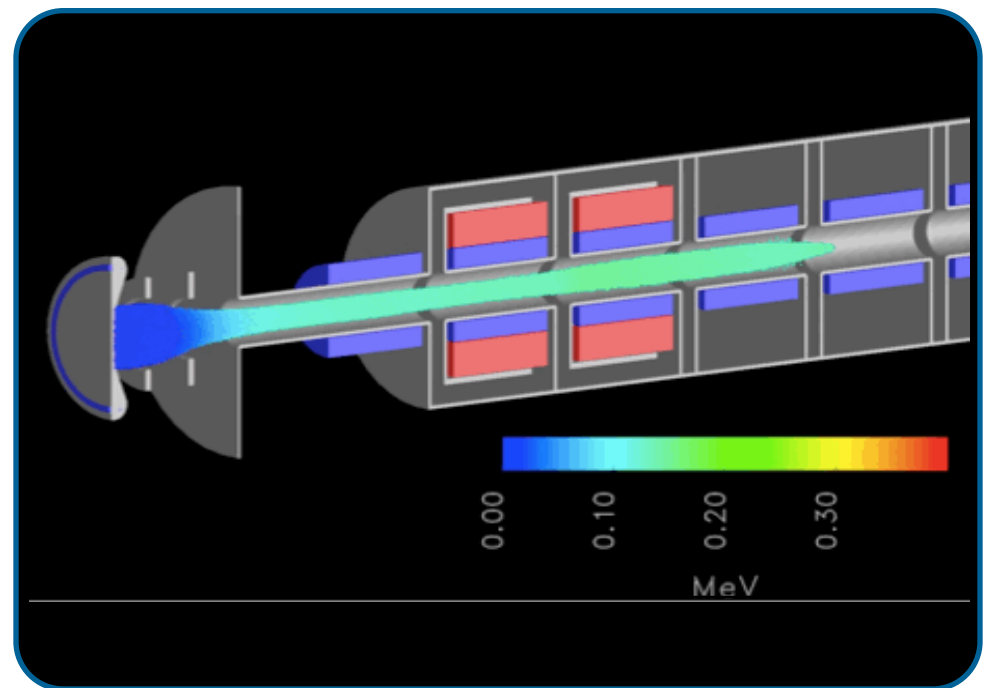
See A. Friedman, *et al.*, *Phys. Plasmas* **17**, 056704 (2010) and references therein.

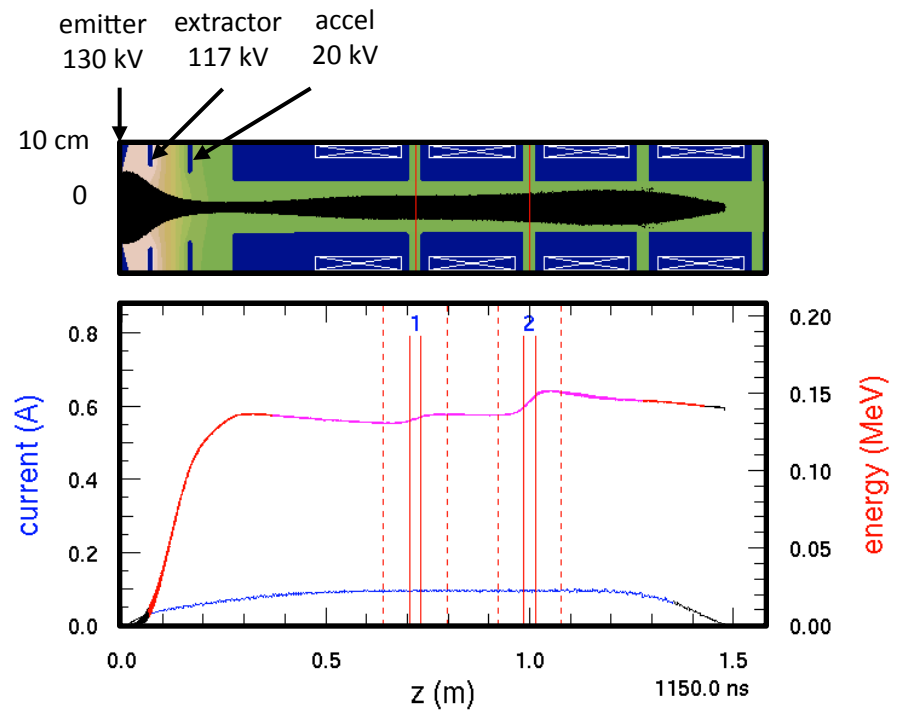# Steps in development of the NDCX-II physics design …

first, use Warp steady-flow "gun" mode to design the injector for a nearly laminar flow

V (kV)
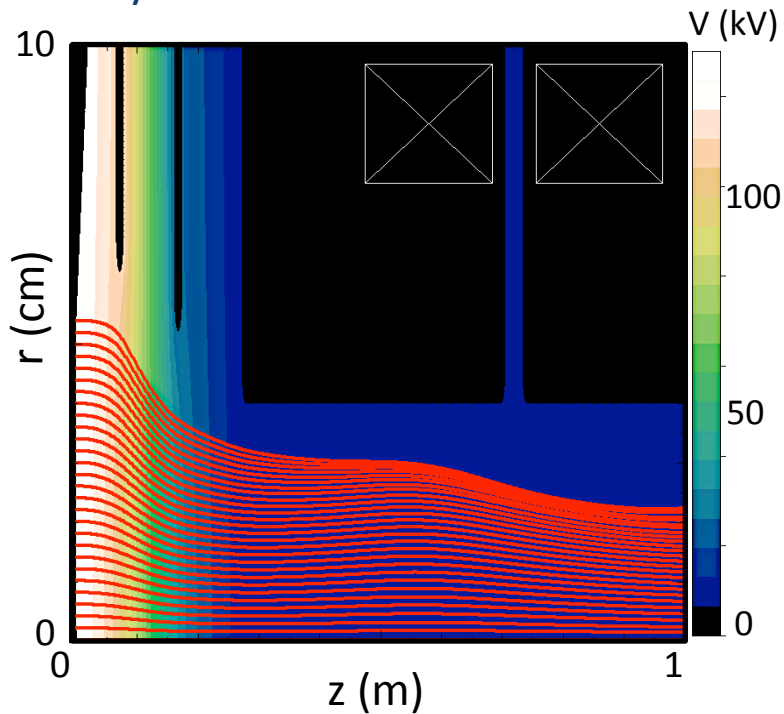
1 mA/cm² Li⁺ ion source

second, carry out a time-dependent *r-z* simulation from the source with Warp
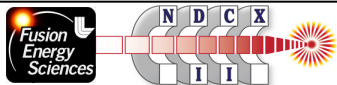
emitter 130 kV   extractor 117 kV   accel 20 kV

40g-12

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Steps in development of the NDCX-II physics design …

third, iterate with ASP to find an acceleration schedule that delivers a beam with a desirable final phase-space distribution

beam length

perveance

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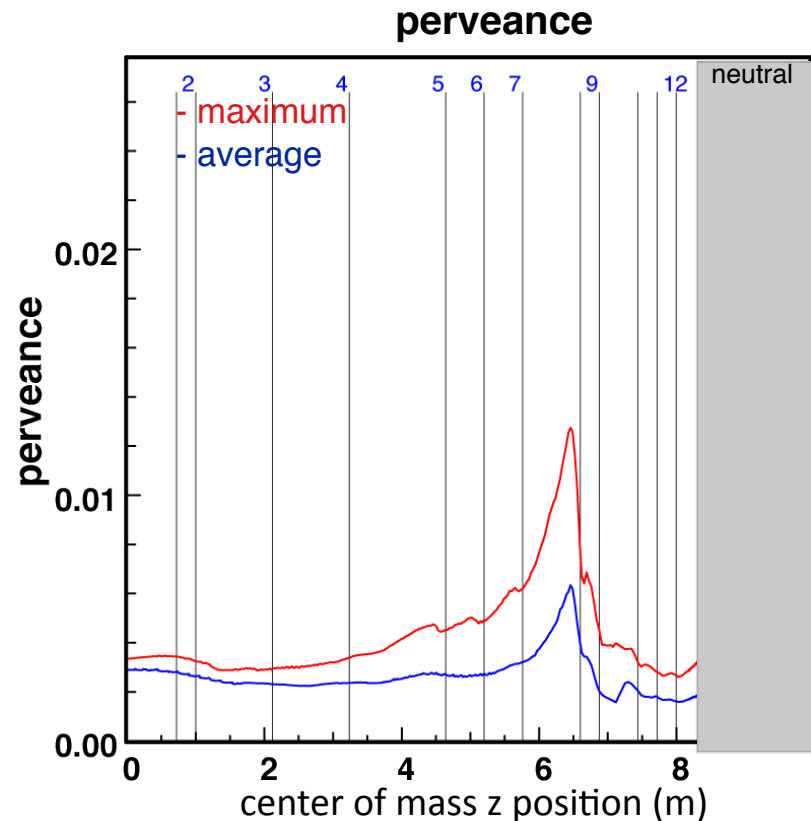
Flat top and ramped voltage waveforms generated on the test stand were used in the physics design
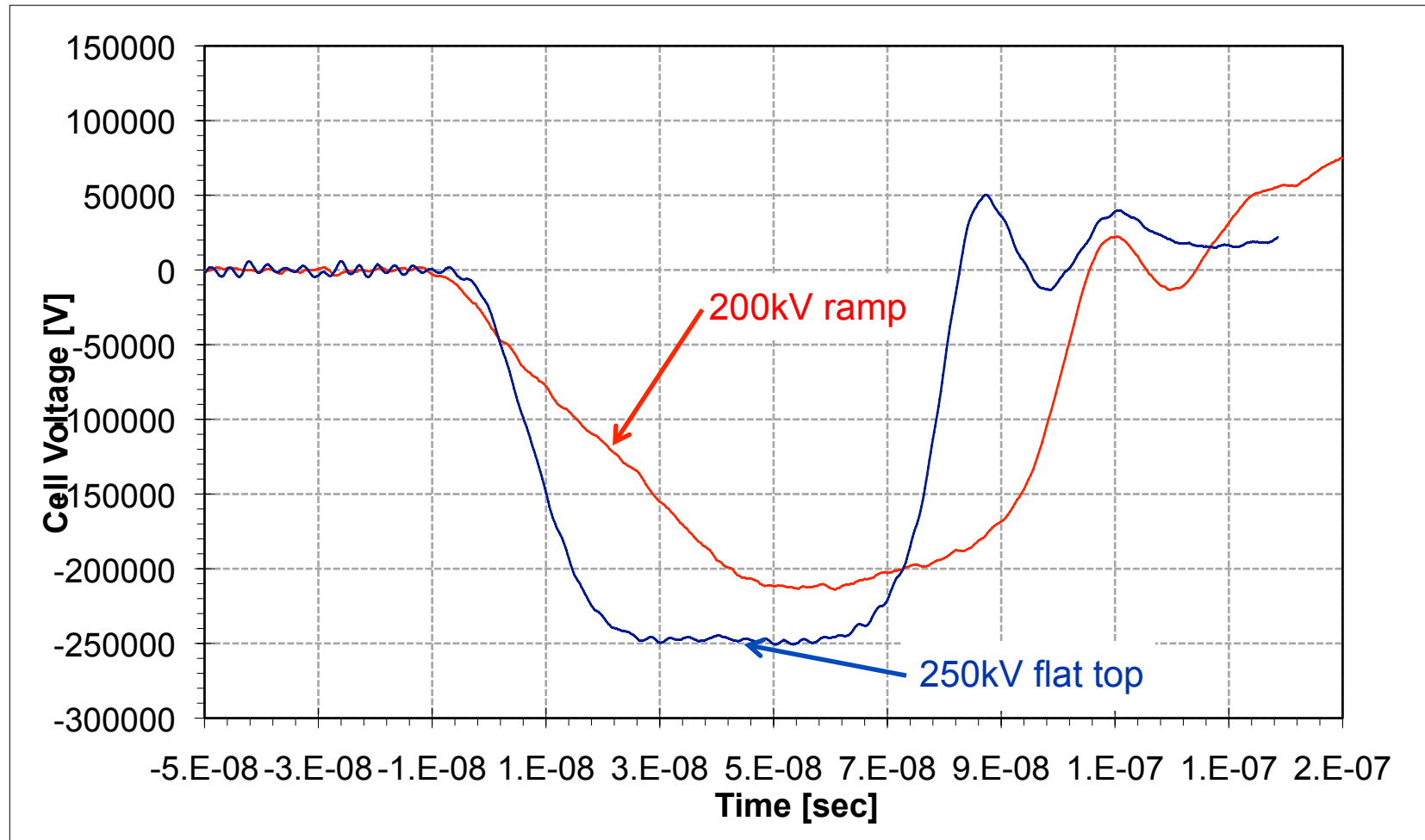
Pulse duration vs. z: the finite length of the gap field folds in

The figure shows a plot of beam duration (ns) versus center of mass z position (m).

Legend:
- **-** time for entire beam to cross a plane at fixed z (red)
- ***** time for a single particle at mean energy to cross finite-length gap (green)
- **+** time for entire beam to cross finite-length gap (blue)
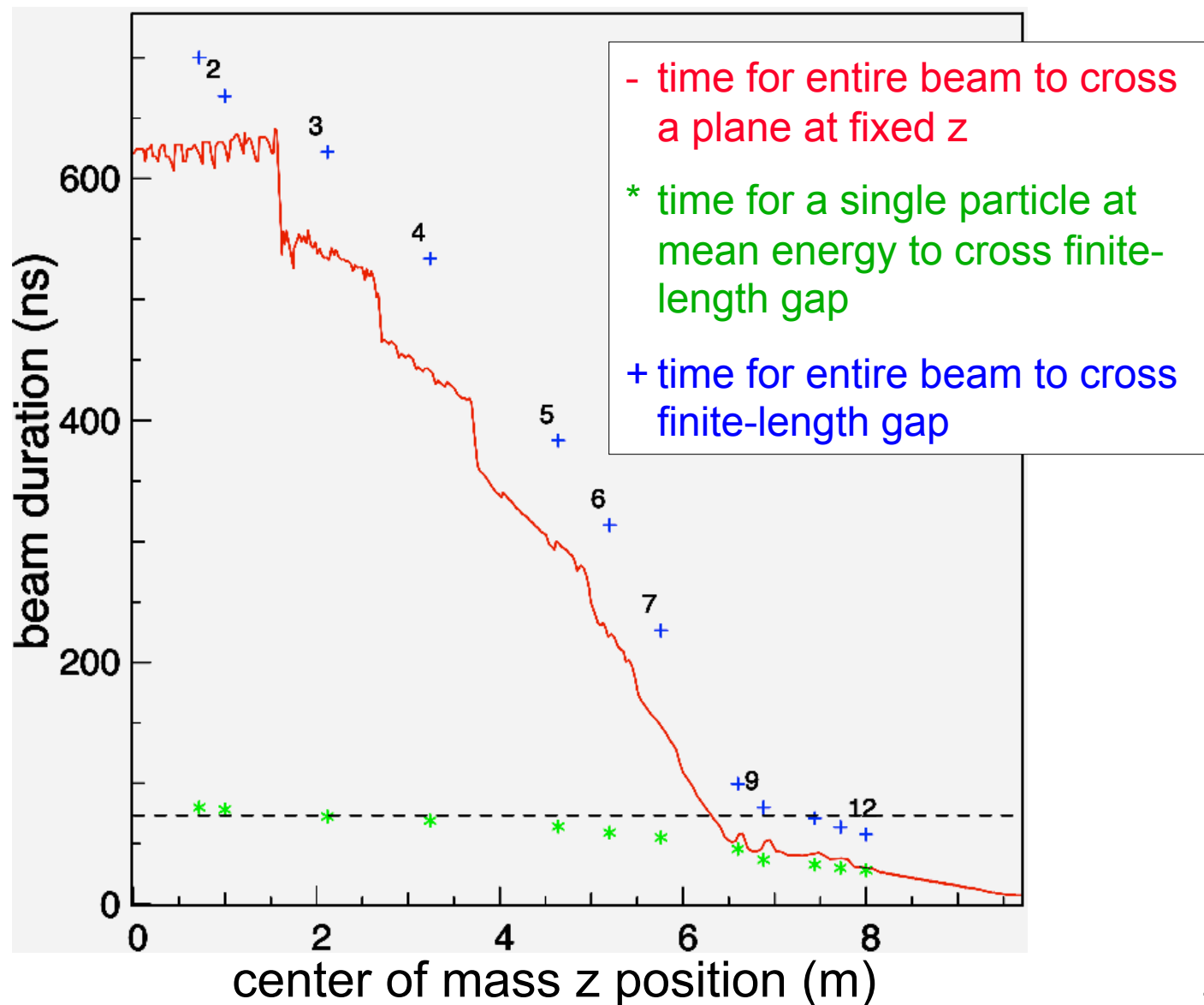
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Steps in development of the NDCX-II physics design …

fifth, adjust transverse focusing to maintain nearly constant radius
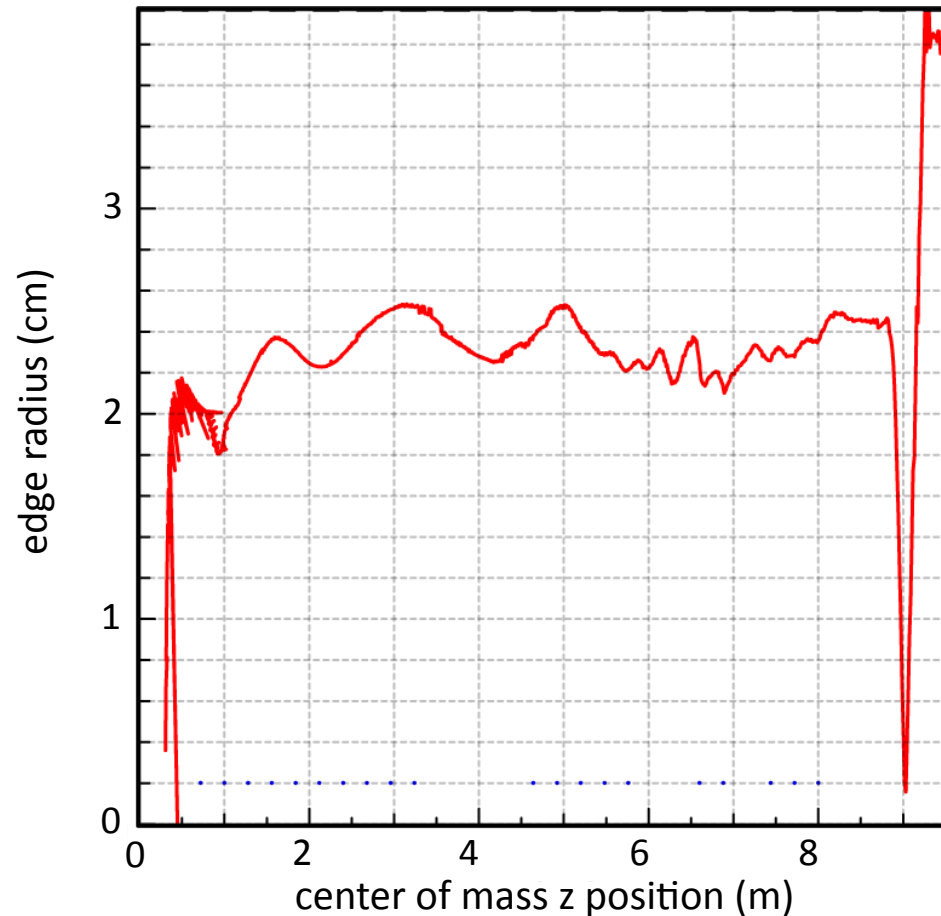
40g.002-12

Snapshots from a Warp (r,z) simulation

compressing
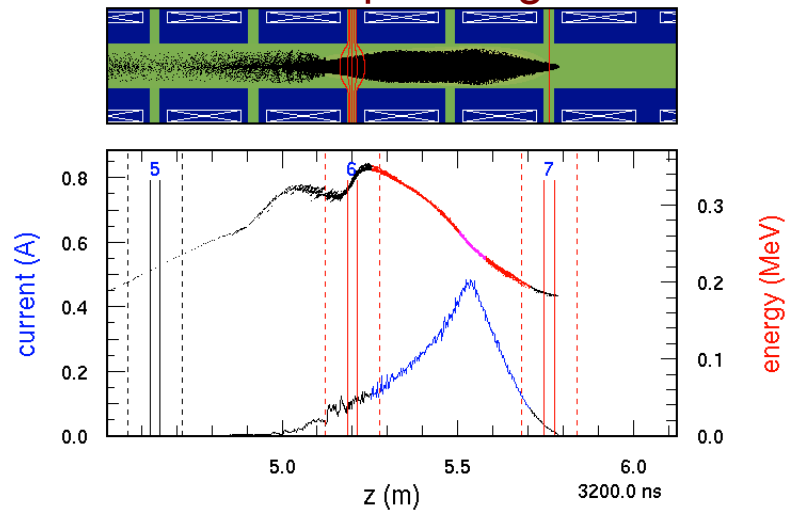
approaching maximum compression
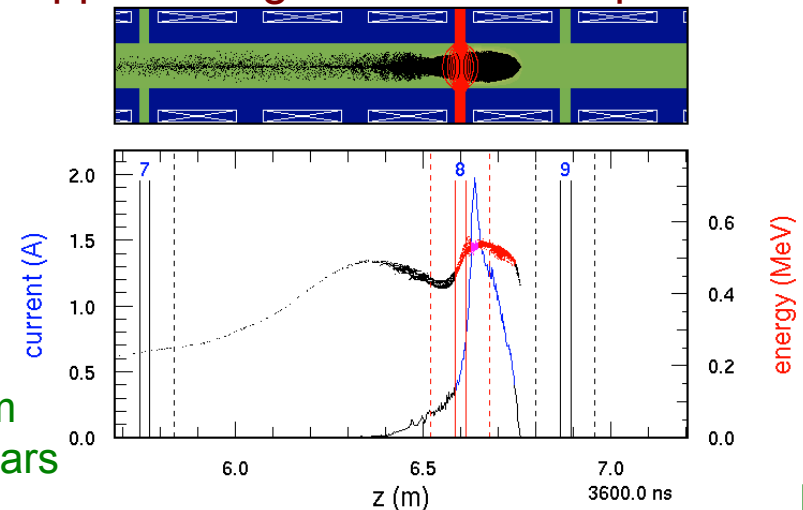
Beam appears long because we plot many particles …

exiting

at focus
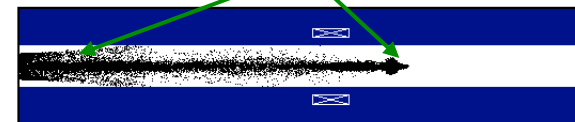
… but current profile shows that it is short

40g-12
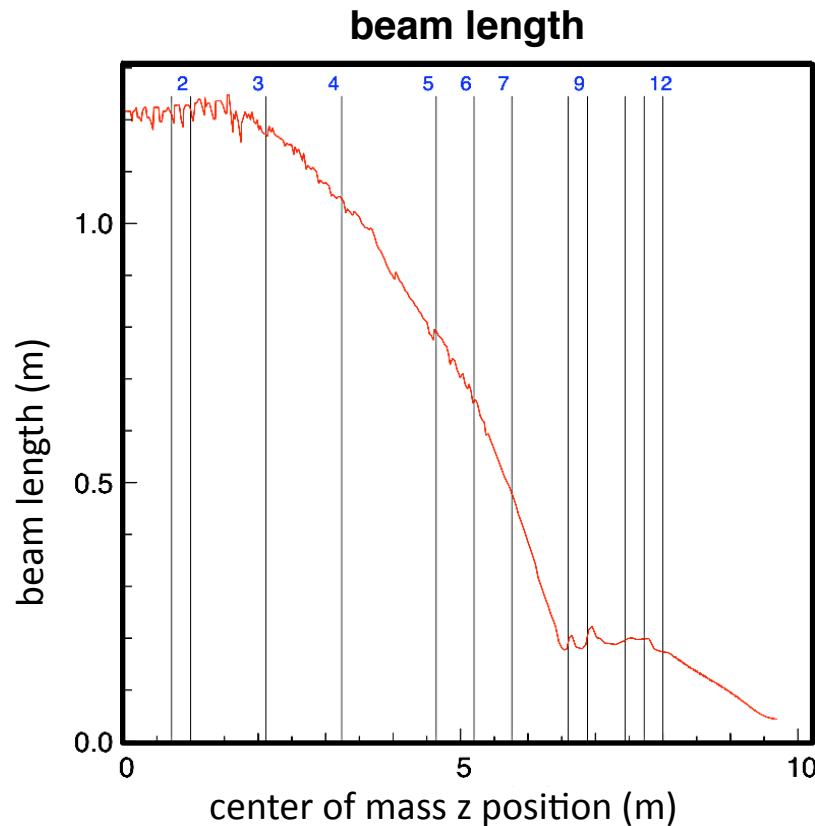
The Heavy Ion Fusion Science Virtual National Laboratory
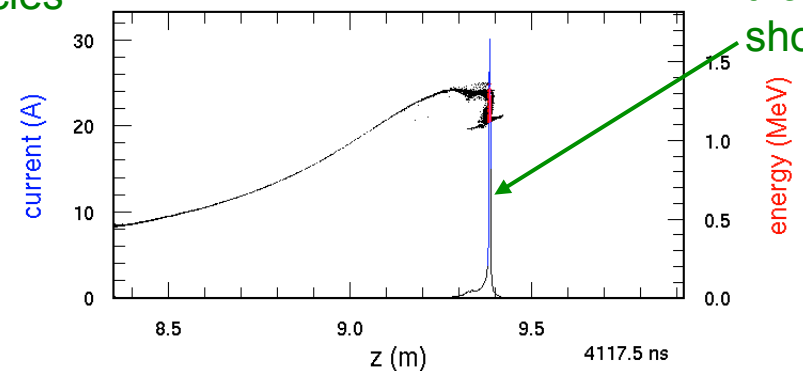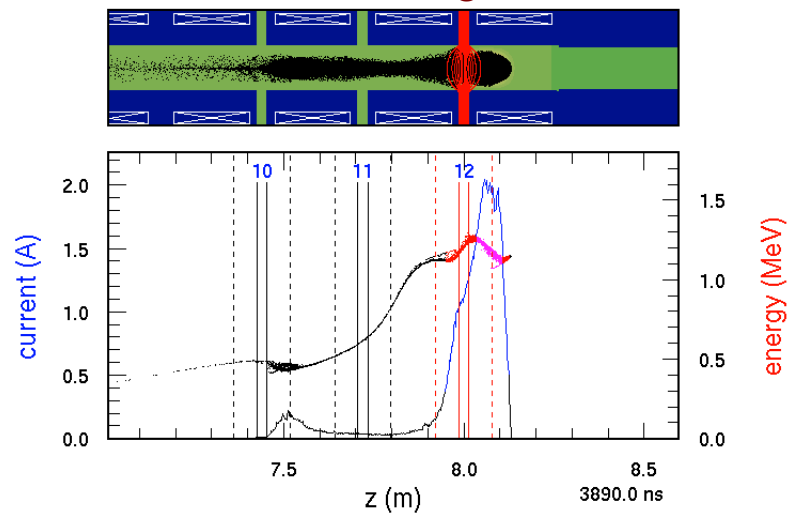
Steps in development of the NDCX-II physics design …

sixth, test sensitivity to random timing error in acceleration waveforms

voltage jitter

2-ns nominal jitter

fluence (J/cm²)

max timing jitter (ns)
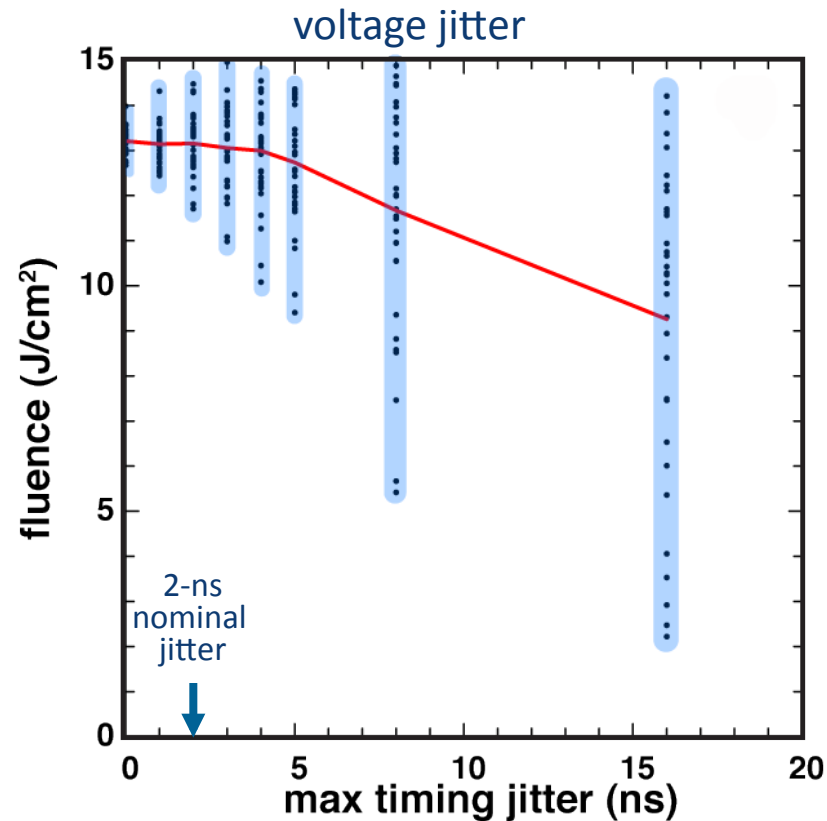
40g-12 with random timing shifts in acceleration voltage pulses

Ensembles of Warp (r,z) runs clarify effects of pulser timing jitter

40g-12
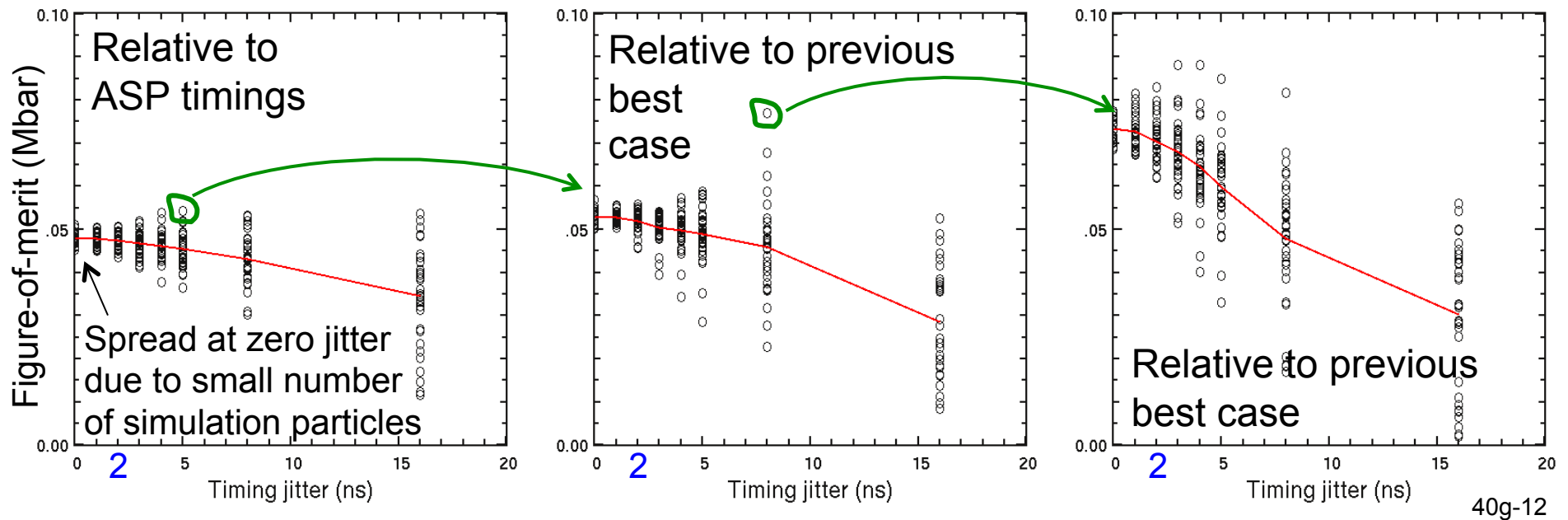
- Random shifts (w/in range shown on abscissa) were imposed on gap firing times; nominal NDCX-II spark-gap jitter is 2 ns

- Figure-of-merit is ~ max pressure (Mbar) in an Aluminum target

- Firing times were developed in ASP code; thus some "perturbed" cases were superior

- We declared the best perturbed case to be the "new nominal"

- There is a tradeoff between performance and insensitivity to jitter

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Steps in development of the NDCX-II physics design …

seventh, test sensitivity to random solenoid misalignments

solenoid alignment

0.5-mm nominal misalignment
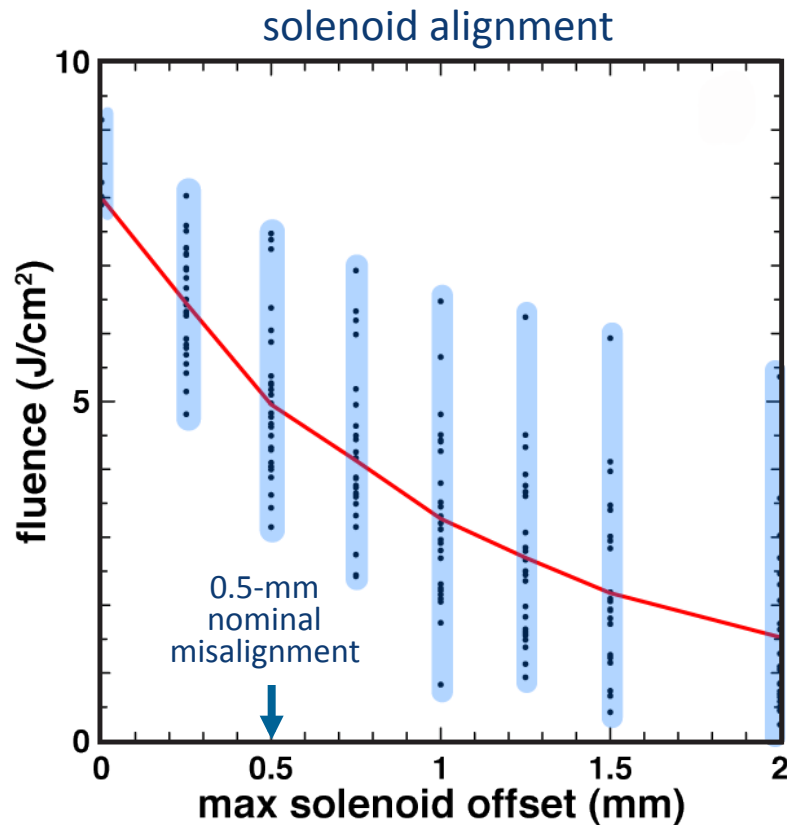
40g-12 with random offsets to both ends of each solenoid

Beam "steering" via dipole magnets will center beam and minimize "corkscrew" distortion.

Warp 3D simulation of 18-cell NDCX-II, including random offsets of solenoid ends by up to 2 mm (0.5 mm is nominal)
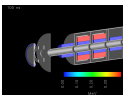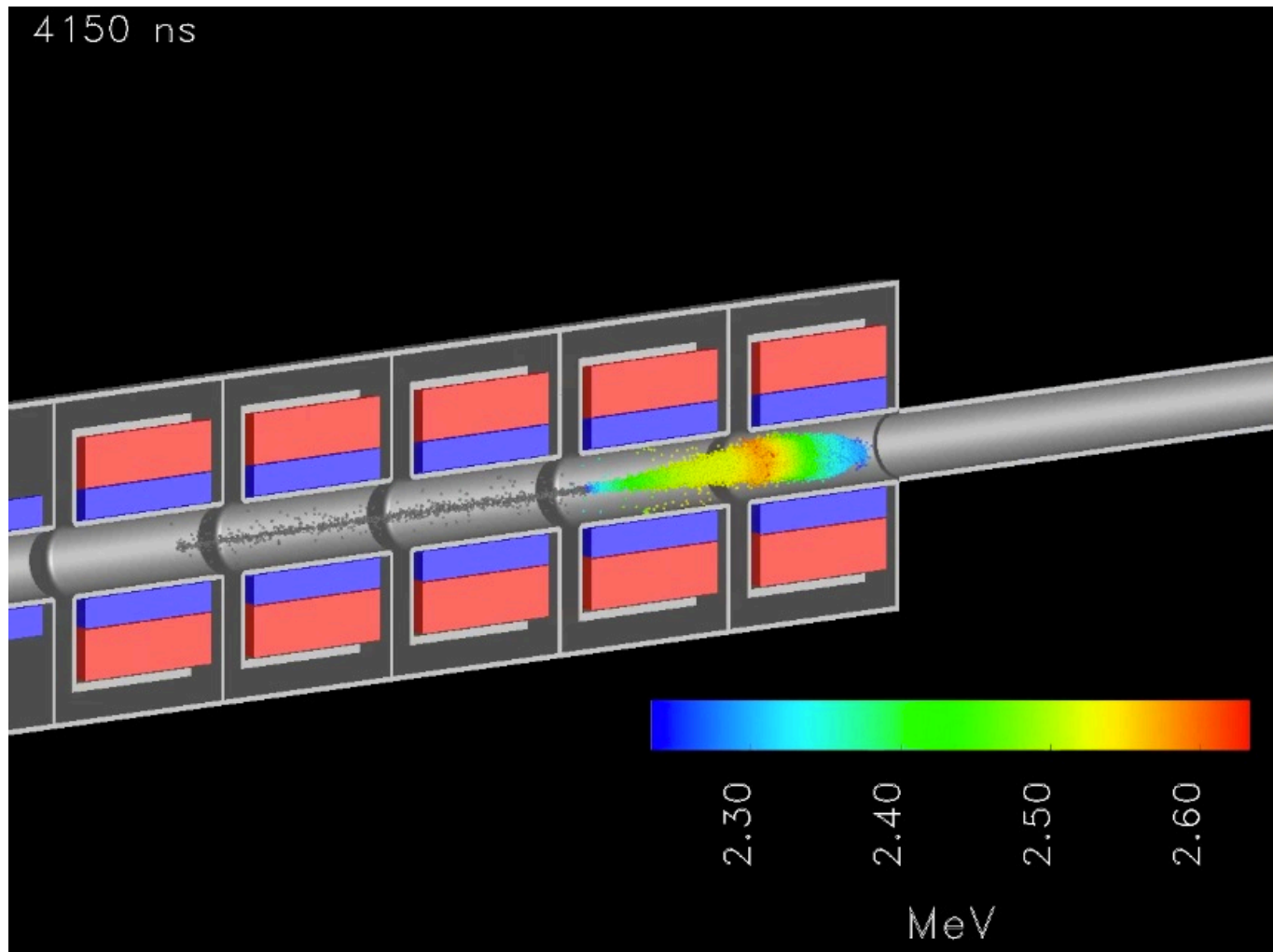
Ndcx40h with 18 active induction cells, 34 periods   simulation and movie from D P Grote

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Warp runs illustrate effects of solenoid alignment errors

plots show beam deposition for three ensembles of solenoid offsets

maximum offset for each case is 0.5 mm

red circles include half of deposited energy

smaller circles indicate hot spots
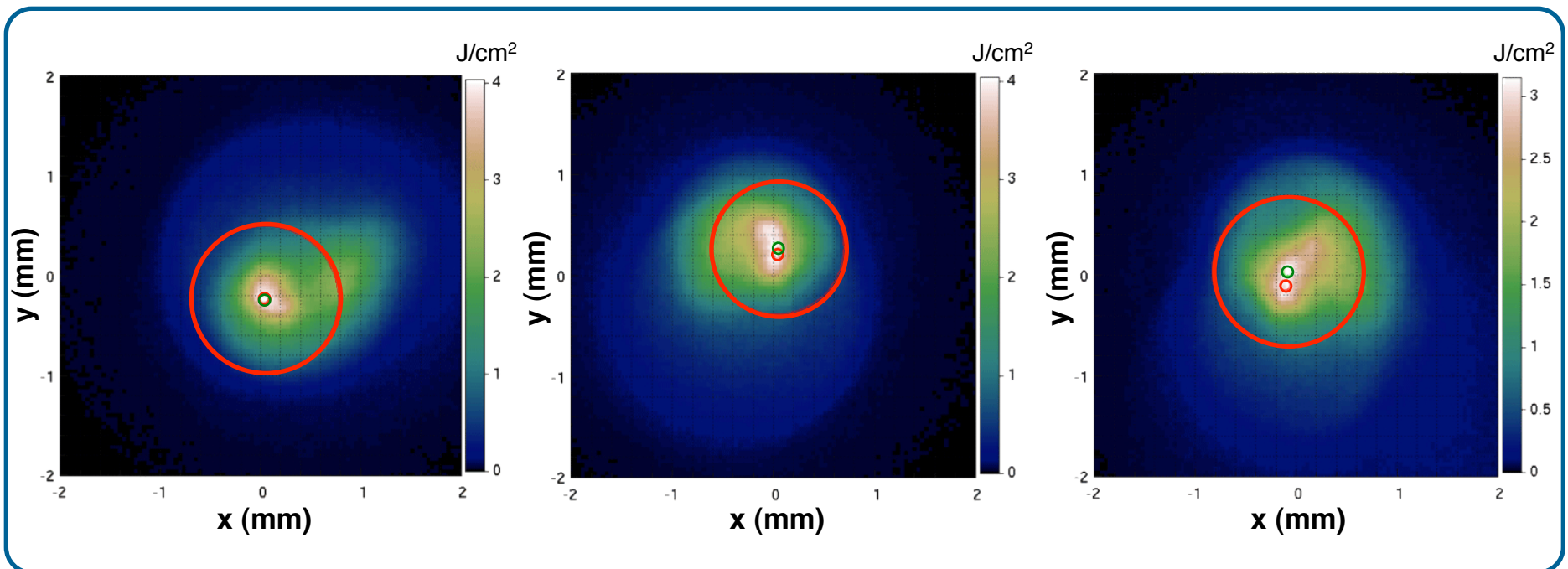
ASP and Warp runs show that steering can improve intensity and stabilize spot location

see Y-J Chen, et al., Nucl. Inst. Meth. in Phys. Res. A 292, 455 (1990)

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"Tuning V" algorithm (modeled in ASP) adjusts "steering" dipole currents so as to minimize a penalty function at the next sensor

x,y vs z trajectories of head, mid, tail particles and the corkscrew size for a typical ASP run
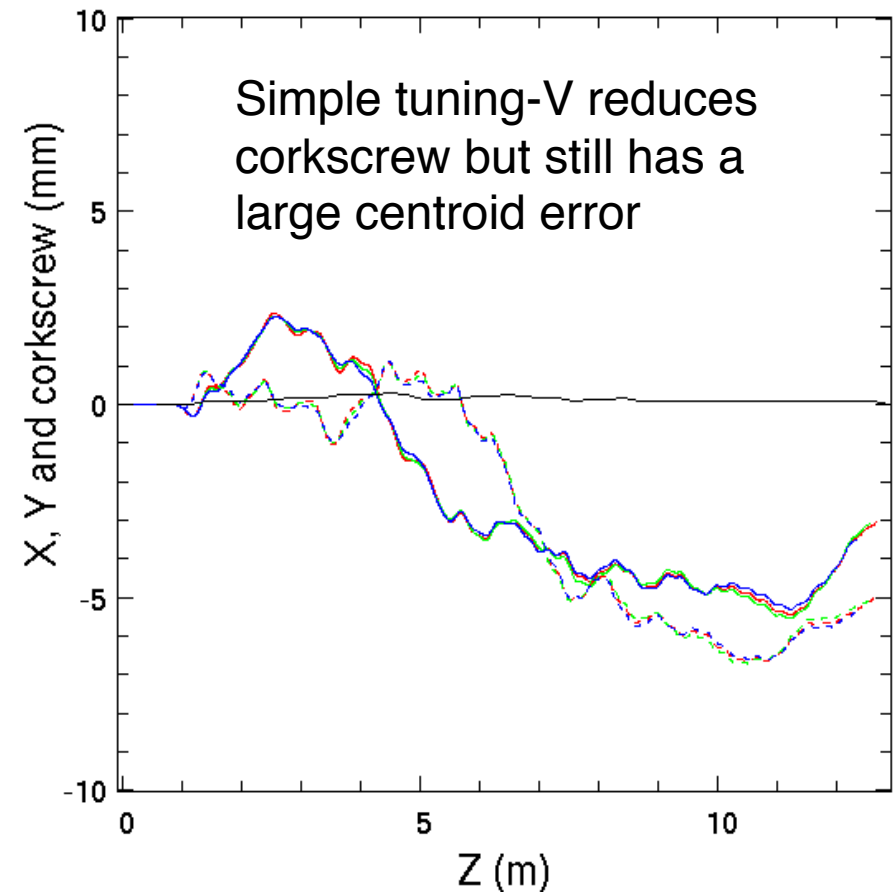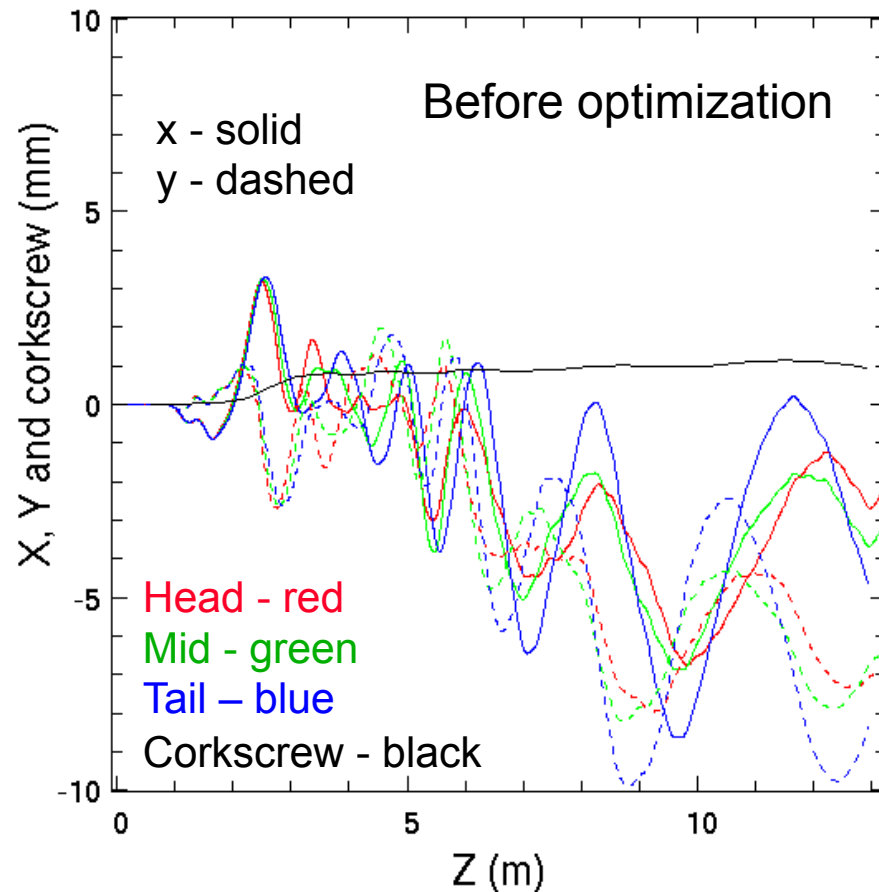
Random offsets of solenoid ends up to 1 mm were assumed; the effect is linear.

To assess steering, we again used the fast ASP code; a tuning algorithm (as in ETA-II, DARHT)[‡] adjusts dipole strengths

Trajectories of head, mid, tail particles, and corkscrew amplitude, for a 34-cell ASP run. Random offsets of solenoid ends up to 1 mm were assumed; the effect is linear.
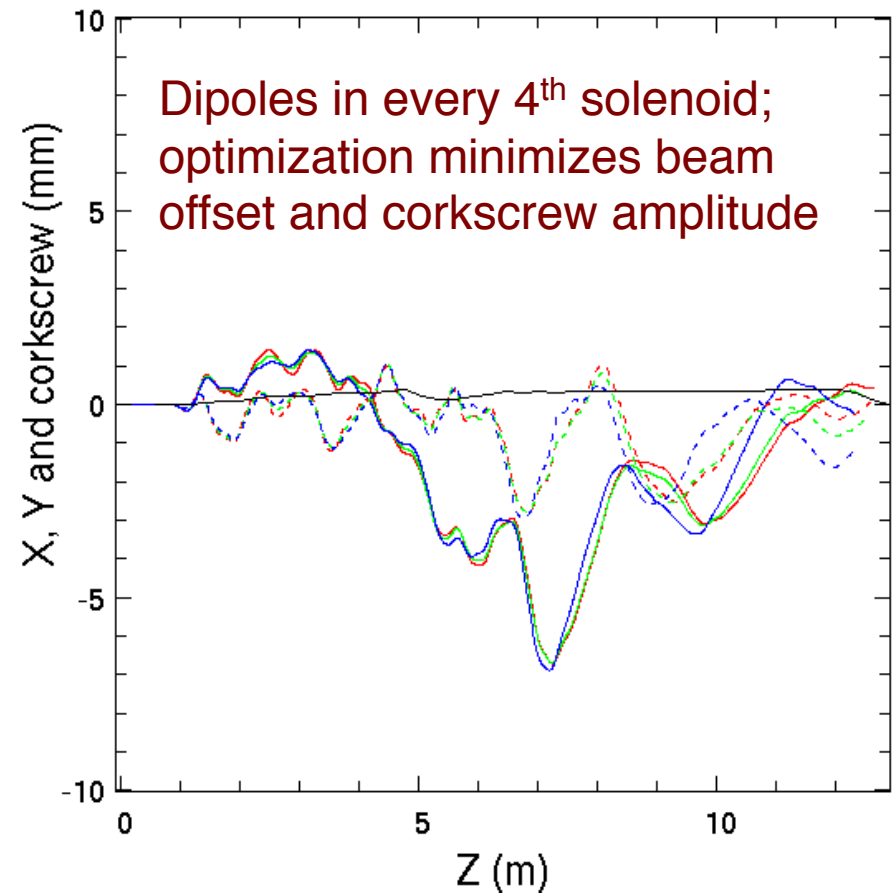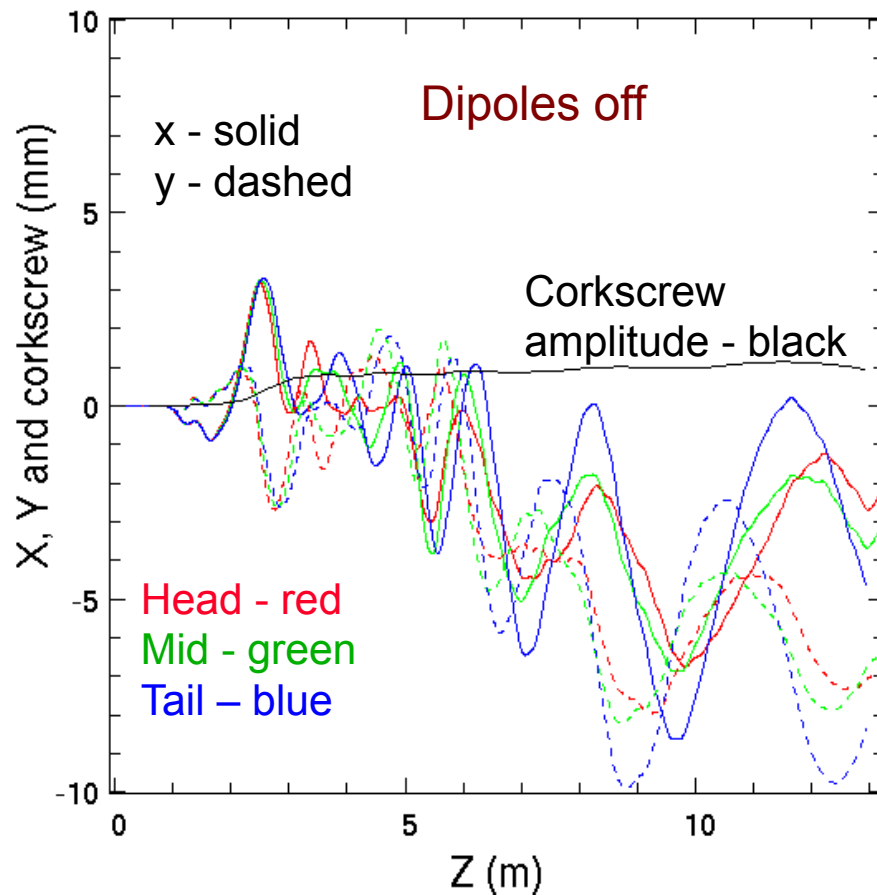
[‡] Y-J. Chen, Nucl. Instr. and Meth. A **398**, 139 (1997).

26b-34
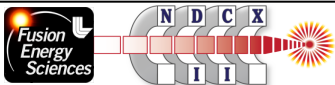
Kinetic plasma simulations of NDCX-II are playing an increasingly important role

- The design of the NDCX-II accelerator and drift line was developed using an ideal-plasma model (without detriment)
    - In the plasma, the beam charge and the potential are forced to zero
    - A smooth transition is made at the plasma edge to model the sheath
- The ideal-plasma model omits physics needed for quantitative prediction of the final focal spot size and pulse duration
    - Imperfect neutralization
    - Sheath behavior when beam enters plasma
    - Electrons streaming upstream as beam enters plasma
    - Electrons following beam through plasma gaps
    - Electron-induced beam focusing in final-focus solenoid fields
    - Plasma instabilities and waves
    - Nonuniform plasma density
- We soon will be designing a large-bore solenoid for the Titan-like chamber, and we need to know how best to inject plasma into it

Simulations include voids in plasma

Final focus solenoid

Gap between FEPS and CAPS

Plasma excluded because B field lines hit the wall

R

Z

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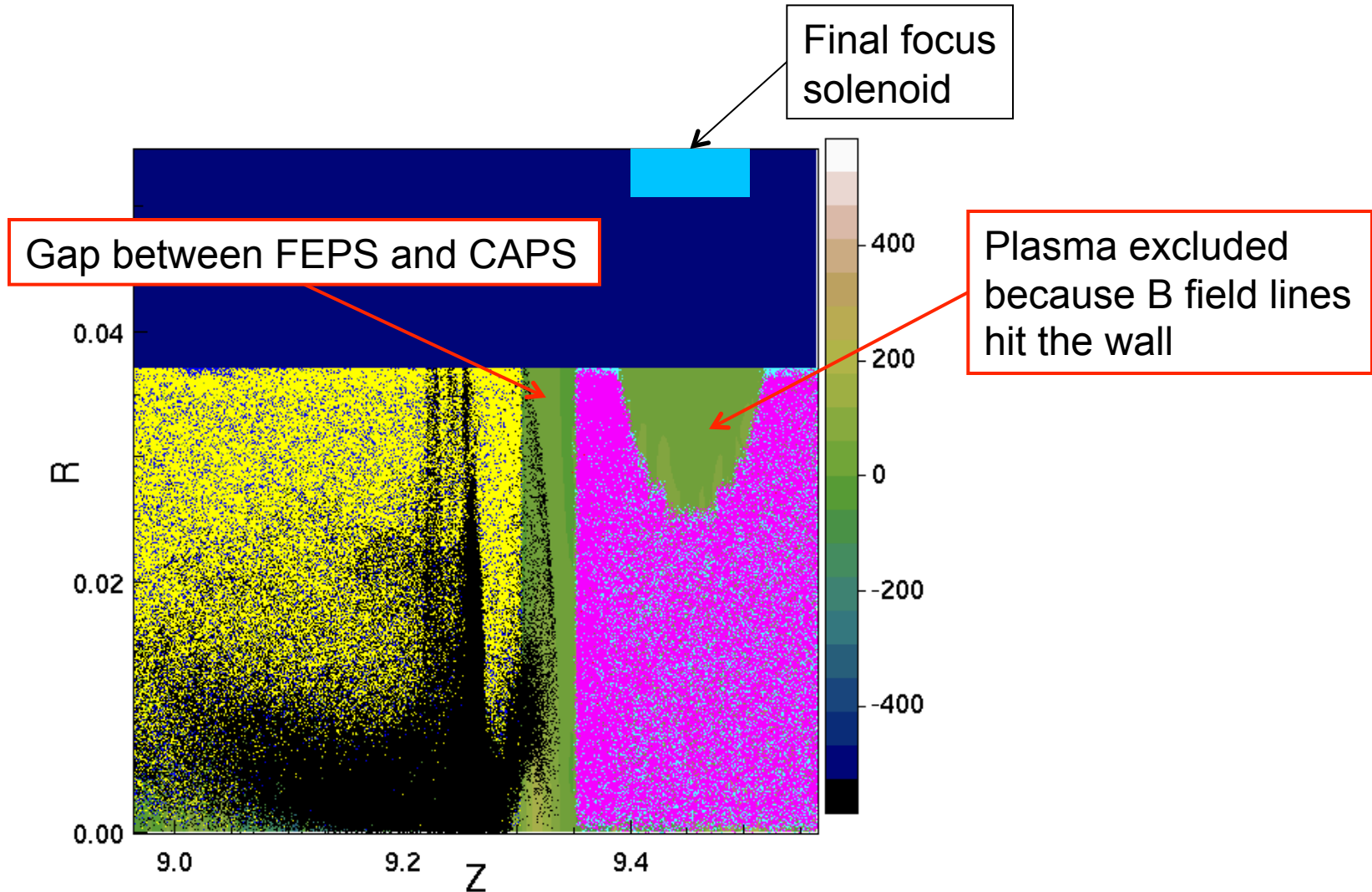
Minimum plasma densities for good performance on target

Examination of the target performance as a function of the FEPS plasma density

Clear degradation below 10^{16} /m^3 (beam density ~6×10^{15} /m^3)

- Pulse compression is slowed, delaying peak compression
- Beam does not focus well

Pulse FWHM

t (ns) vs FEPS density (log10(N/m^3))
ndcx49c2, 12 active cells

Spot half radius

R (mm) vs FEPS density (log10(N/m^3))
ndcx49c2, 12 active cells

Peak deposition, time integrated

Peak fluence (J/cm-sq) vs FEPS density, (log10(N/m^3))
ndcx49c2, 12 active cells

Estimated max pressure in target

Max pressure (MBar) vs FEPS density, (log10(N/m^3))
ndcx49c2, 12 active cells
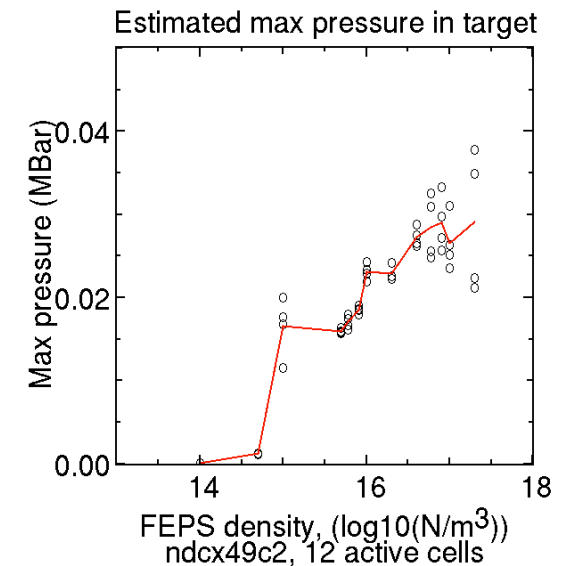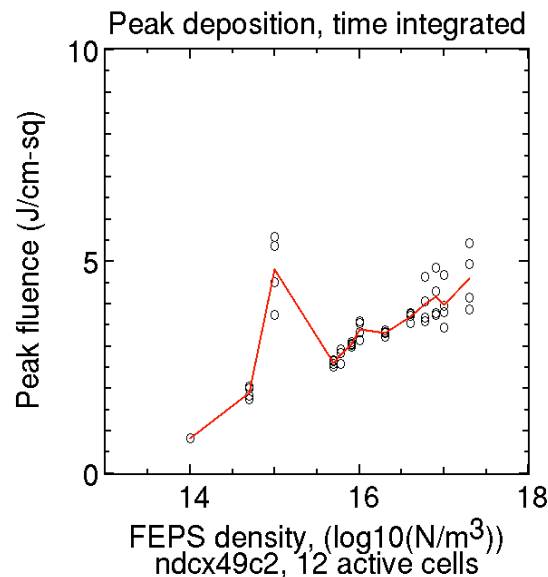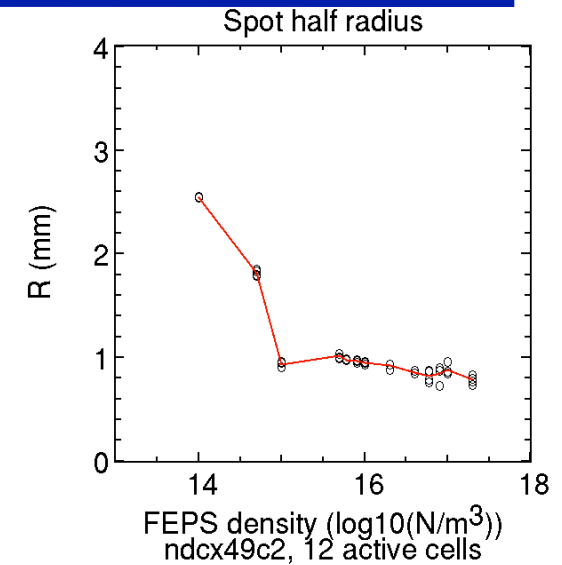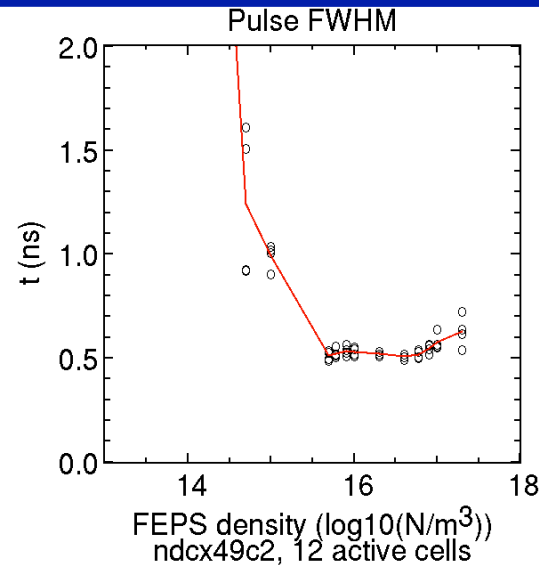
Near-term prospects

Things we need to measure, and the diagnostics we'll use

Non-intercepting (in multiple locations):

- <u>Accelerating voltages</u>: voltage dividers on cells
- <u>Beam transverse position</u>: four-quadrant electrostatic capacitive probes
- <u>Beam line charge density</u>: capacitive probes
- <u>Beam mean kinetic energy</u>: time-of-flight to capacitive probes

Intercepting (in two special "inter-cell" sections):

- <u>Beam current</u>: Faraday cup
- Beam emittance: two-slit or slit-scintillator scanner
- <u>Beam profile</u>: scintillator-based optical imaging
- <u>Beam kinetic energy profile</u>: time-of-flight to Faraday cup
- Beam energy distribution: electrostatic energy analyzer

(<u>Underlined items</u> will be available at commissioning)

"Physics risks" concern beam intensity on target, not risk to the machine due to beam impact

- Alignment errors exceeding nominal 0.5 mm
  - Machine usable with larger errors with intensity degradation
  - Beam "steering," using dipoles in diagnostic cells, can mitigate "corkscrew" deformation of beam
  - Off-center beam, if reproducible, is not a significant issue
- Jitter of spark-gap firing times exceeding nominal 2 ns
  - Slow degradation of performance with jitter expected, per simulations
  - Similar slow degradation as waveform fidelity decreases
- Source emission non-uniform, or with density less than nominal 1 mA/cm^2
  - Simulations show a usable beam at 0.5 mA/cm^2
  - Can run in this mode initially, to maximize source lifetime
  - Space-charge-limited emission mode offers best uniformity
- Imperfect neutralization because final-focus solenoid not filled with plasma
  - Build and use a larger-radius solenoid (as part of "Titan-like" chamber)

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NDCX-II, when mature, should be far more capable than NDCX-I

	NDCX-I (typical bunched beam)	NDCX-II 12-cell (ideal*)
Ion species	K^+ (A=39)	Li^+ (A=7)
Total charge	15 nC	50 nC
Ion kinetic energy	0.3 MeV	1.25 MeV
Focal radius (containing 50% of beam)	2 mm	0.6 mm
Bunch duration (FWHM)	2 ns	0.6 ns
Peak current	3 A	38 A
Peak fluence (time integrated)	0.03 J/cm^2	8.6 J/cm^2
Fluence within a 0.1 mm diameter spot	0.03 J/cm^2 (50 ns window)	5.3 J/cm^2 (0.57 ns window)
Fluence within 50% focal radius and FWHM duration ($E_{kinetic}$ x I x t / area)	0.014 J/cm^2	1.0 J/cm^2

* NDCX-II estimates of ideal performance are from (r,z) Warp runs (no misalignments), and assume uniform 1 mA/cm^2 ion emission, no timing or voltage jitter in acceleration pulses, no jitter in solenoid excitation, and perfect beam neutralization; they also assume no fine energy correction (e.g., tuning the final tilt waveforms)

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Warp (r,z) simulation of the 3.1 MeV configuration with 21 active cells
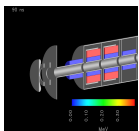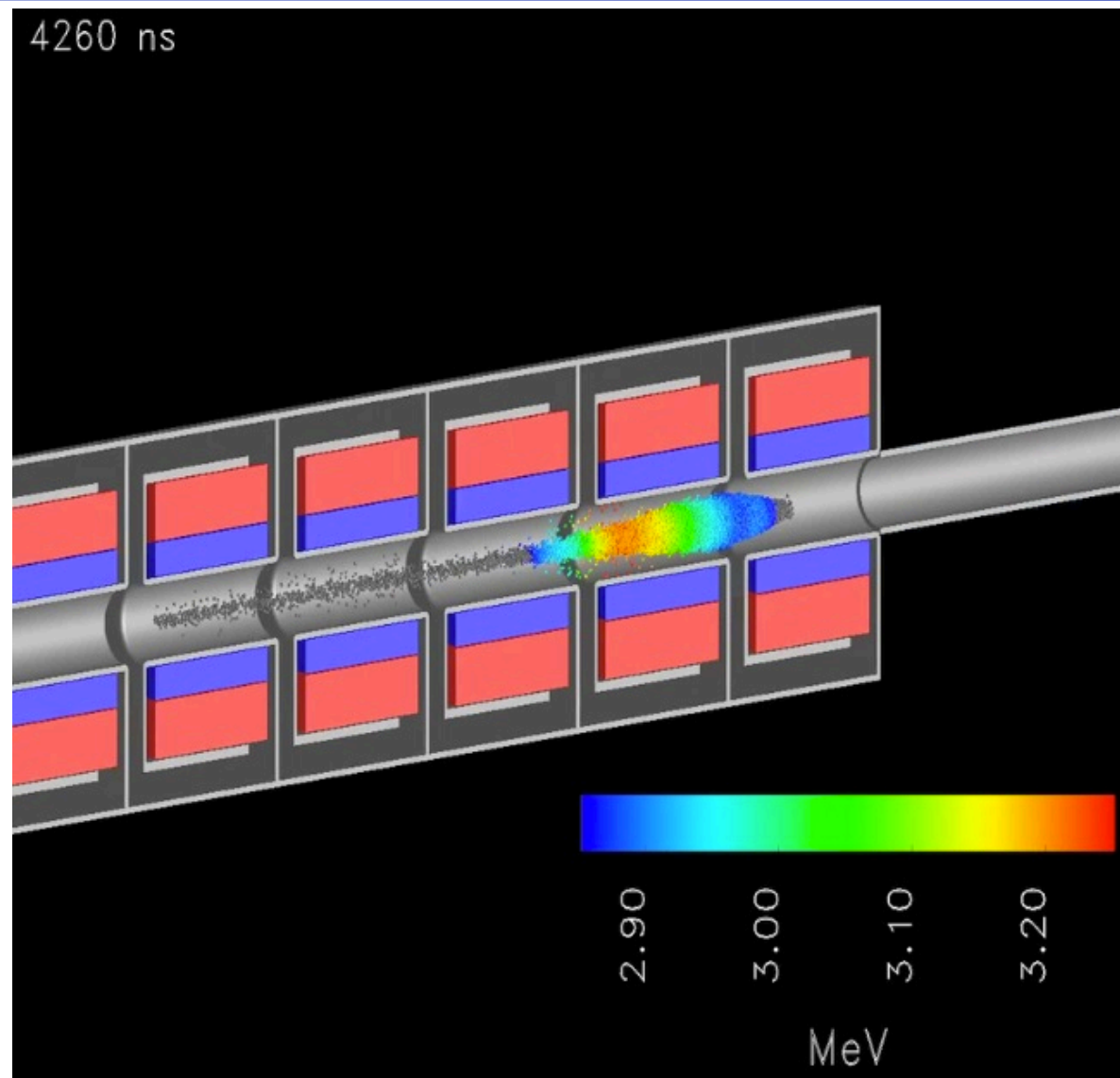
ndcx40k with 37 lattice periods and 21 active induction cells   simulation and movie from D P Grote

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Assuming ideal neutralization, pulse duration in NDCX-II varies roughly inversely with kinetic energy — with 46 induction cells, beam phase space appears consistent with ~100 ps FWHM
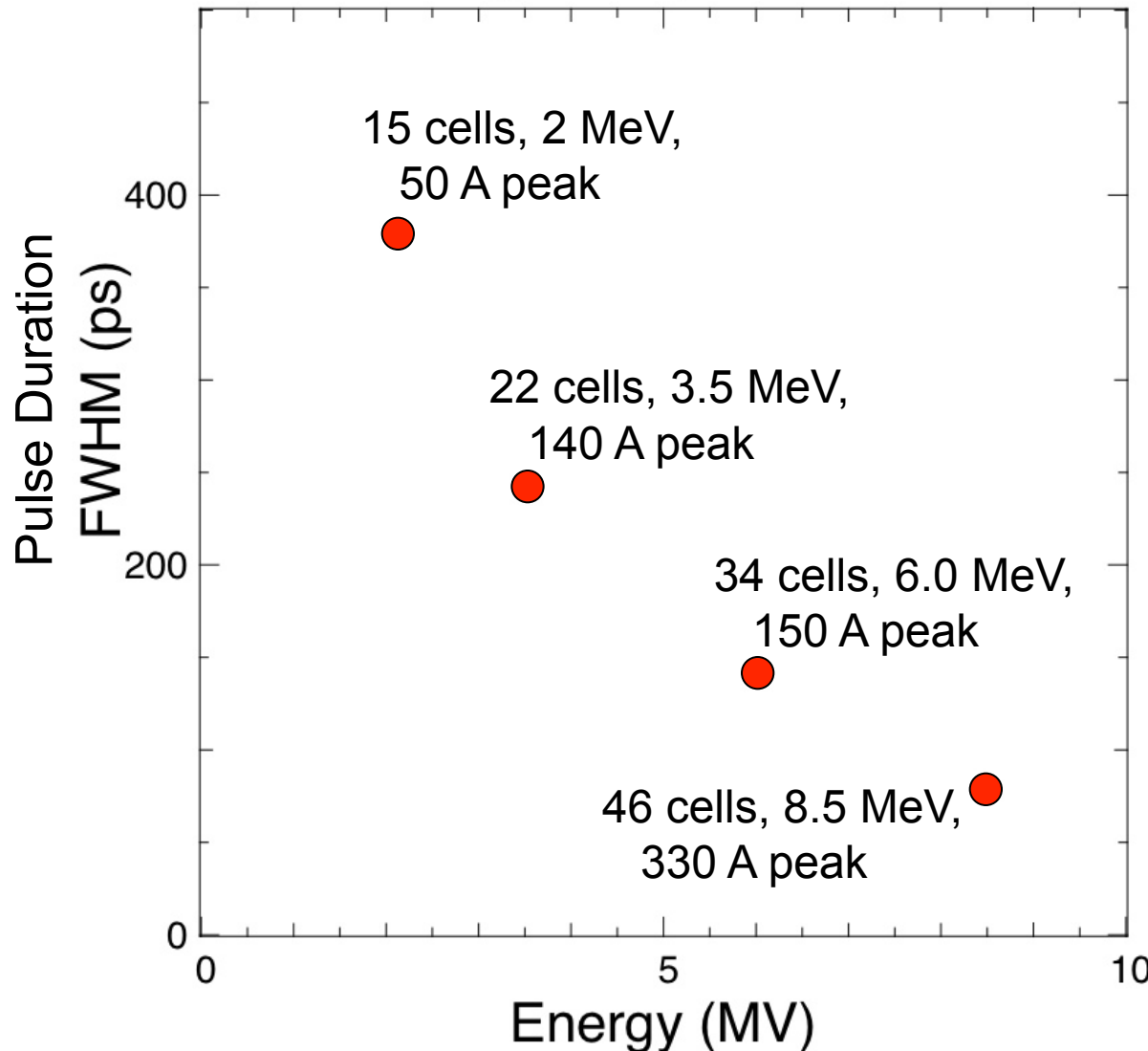
Results of Warp simulations, using highly optimized waveforms and assuming ideal pulse timing, voltage accuracy, neutralization, and source uniformity

- Separate studies have examined effects of:
- timing jitter and voltage ripple in accelerating waveforms
- injector voltage ripple
- misalignments
- source emission (2 mA/cm^2 assumed here)
- source temperature
- Modest degradation due to these effects is observed

Plot labels:
- 15 cells, 2 MeV, 50 A peak
- 22 cells, 3.5 MeV, 140 A peak
- 34 cells, 6.0 MeV, 150 A peak
- 46 cells, 8.5 MeV, 330 A peak

Y-axis: Pulse Duration FWHM (ps)
X-axis: Energy (MV)

Beam physics experiments

HIF-relevant beam experiments on NDCX-II can study …

- How well can space charge "stagnate" the compression to produce a "mono-energetic" beam at the final focus?

- How well can we pulse-shape a beam during drift compression (vs. the Robust Point Design's "building blocks")?

J. W-K. Mark, et al., AIP Conf. Proc **152**, 227 (1986)
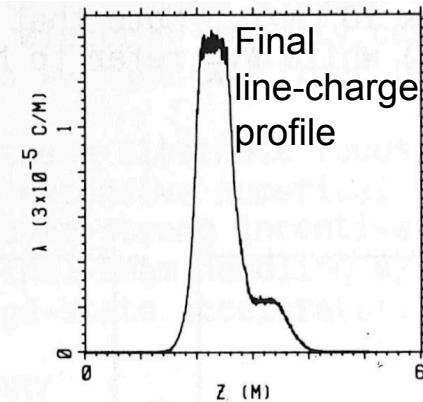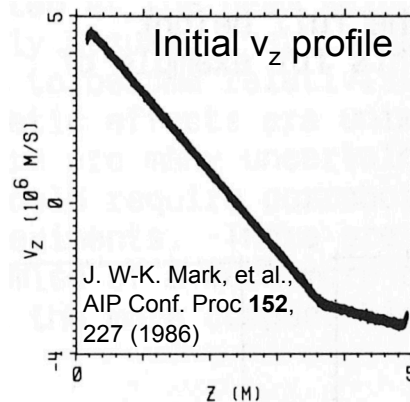
- How well can we compress a beam while bending it?:
  - "achromatic" design, so that particles with all energies exit bend similarly
  - or, leave some chromatic effect in for radial zooming
  - emittance growth due to dispersion in the bend
- Are there any issues with final focus using a set of quadrupole magnets?

> Most dimensionless parameters (perveance, "tune depression," compression ratio, etc.) will be similar to, or more aggressive than, those in a driver.

NDCX-II will be an exciting platform for beam physics studies (many of them relevant to an HIF driver)

- NDCX-II operation embodies collective beam dynamics:
  - Space-charge force ("perveance") is very large
  - Driver-like compression of non-neutral and neutralized beams
  - Removal of velocity tilt by space-charge force, to achieve "stagnation"
  - Longitudinal waves are evident
- Non-ideal effects include:
  - Emittance growth (phase-space dilution), "halo" formation
  - Beam - plasma interactions and instabilities
  - Aberrations in final focus
- Add-on hardware could enable studies of:
  - Collective focusing of ion beams
  - Intense beam transport in quadrupoles
  - Beam dynamics in bends
- Beam diagnostics will be developed and improved

NDCX-II will enable greater understanding of beams in plasmas

Electromagnetic fields are excited by a moving beam in a magnetized plasma:

Wave field (can extend far outside the bunch)

Local field (falls off rapidly outside the bunch)
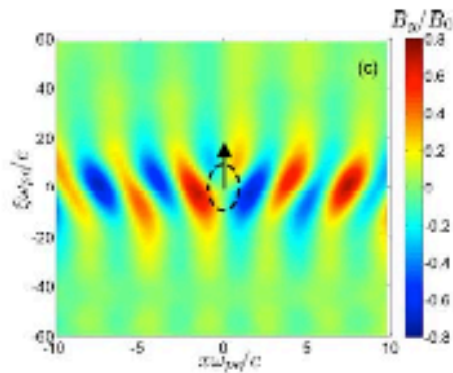
Can be used for diagnostics
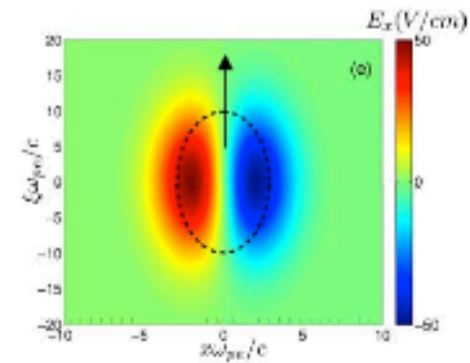
Can provide bunch focusing

M. Dorf, I. Kaganovich, E. Startsev, and R. C. Davidson, Phys. Plasmas **17**, 023103 (2010).

M. Dorf, I. Kaganovich, E. Startsev, and R. C. Davidson, PRL **103**, 075003 (2009)

Review paper: I. D. Kaganovich, *et al.*, Phys. Plasmas **17**, 056703 (2010)

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The "Robertson lens" offers collective focusing in a quasi-neutral system

- An ambipolar electrostatic field brings both species to a common focus
- For a given focal length, the required B_0 is smaller by a factor of $(m_e/m_i)^{1/2}$

solenoidal coil

E_z

neutralized ion beam

e^-, i^+

E_r

focal point

(from Kraft paper)
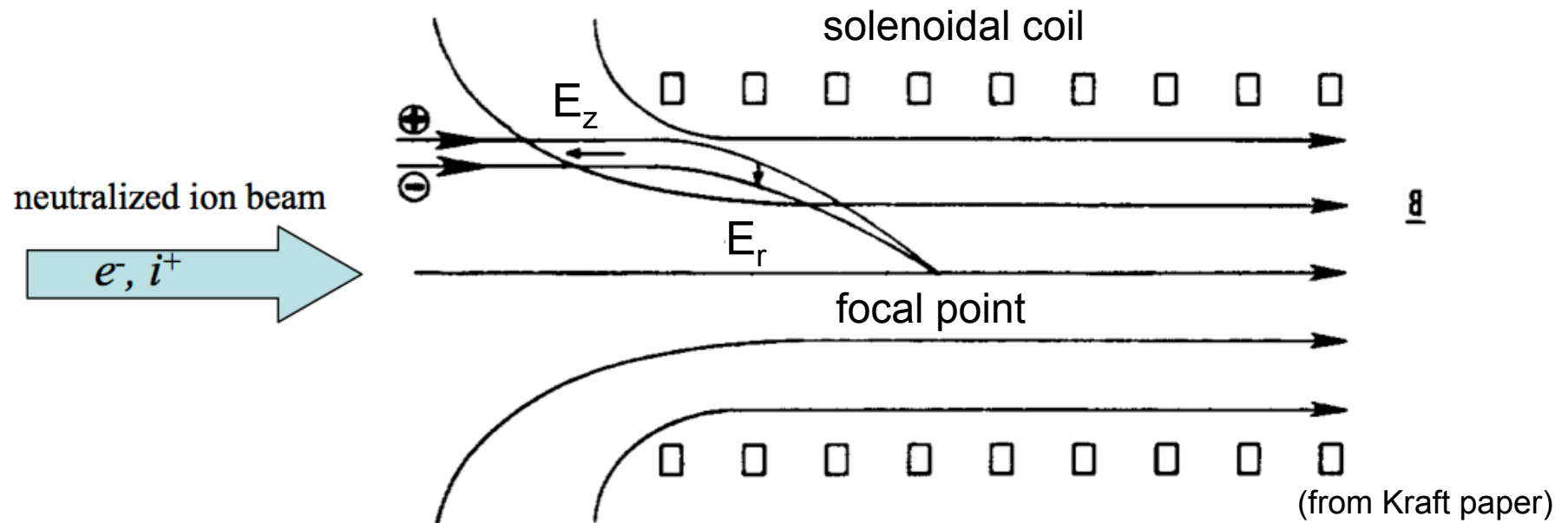
Focusing force on beam: $F_r = -\dfrac{r}{4} m_i \Omega_e \Omega_i \quad (\Omega_i = Z_b e B_0 / m_i c)$

References: S. Robertson, *Phys. Rev. Lett.* **48**, 149 (1982).
R. Kraft, B. Kusse, & J. Moschella, *Phys. Fluids* **30**, 245 (1987).

requires:
$r_b << c/\omega_{pe}$
$\omega_{pe} >> \omega_{ce}$

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NDCX-II Layout at LBNL

long-pulse
voltage sources

ATA Blumlein
voltage sources

Li+ ion
injector

final focus solenoid
and target chamber
(existing)

pulsers for
solenoids

ATA induction cells
with pulsed
2.5 T solenoids

oil-filled ATA
transmission lines

neutralized drift compression
line with plasma sources

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NDCX-II Layout – Red boxes showing the remaining hardware to be installed between Jan–Mar 2012 (using < $500k of HIF program funds)

long-pulse voltage sources

ATA Blumlein voltage sources

Li⁺ ion injector

final focus solenoid and target chamber (existing from NDCX-I)

pulsers for solenoids

ATA induction cells with pulsed 2.5 T solenoids

oil-filled ATA transmission lines

neutralized drift compression line with plasma sources

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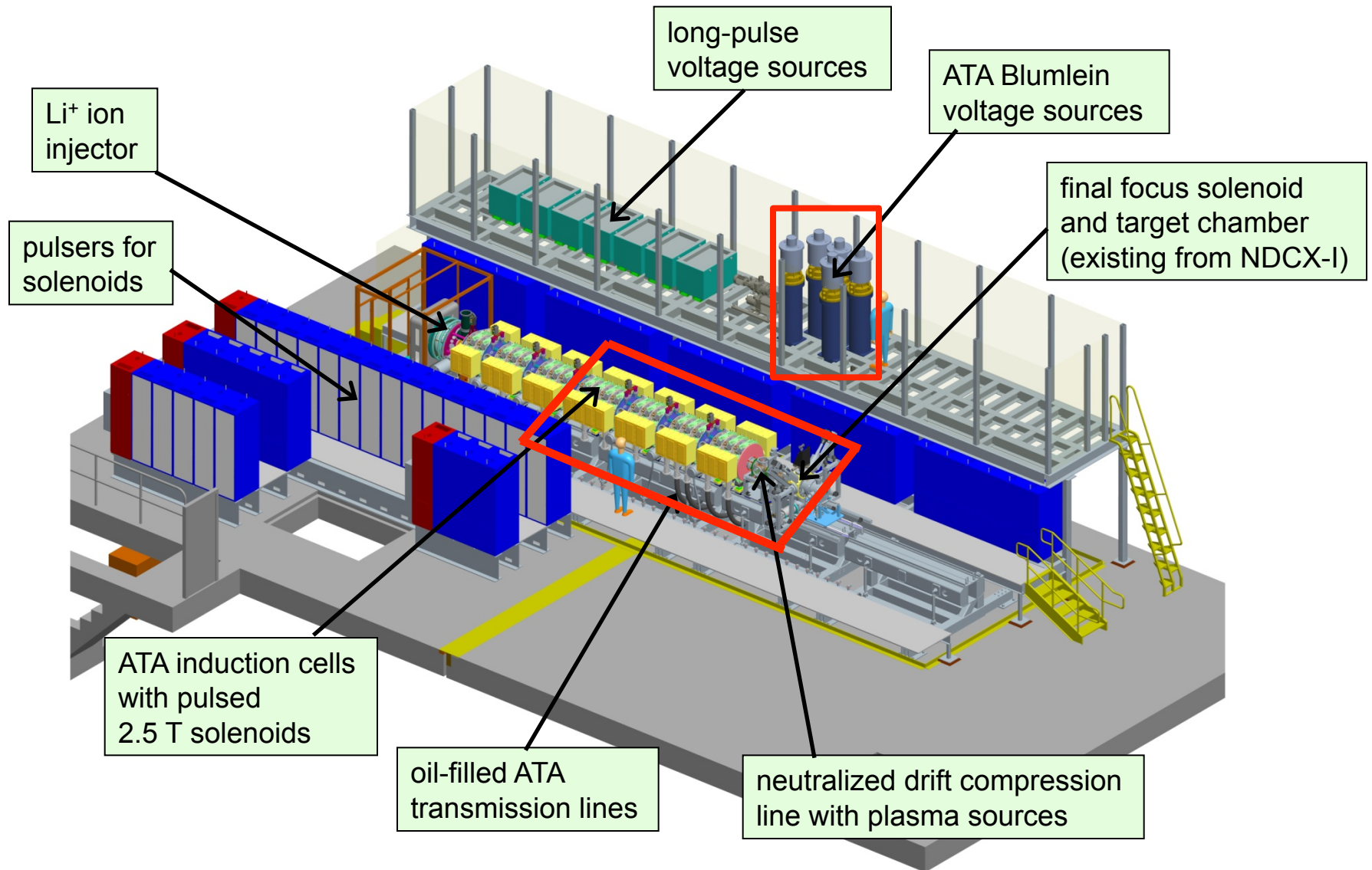
The NDCX-II Project Scope and Deliverables

- **Leveraging the available induction modules and pulsers from the retired ATA electron linac at LLNL to build a new induction linear accelerator**

- **Project budget is $11M (contingency included)**

- **Project schedule is July 1, 2009 to March 31, 2012**

- **Deliverables and Acceptance Criteria:**

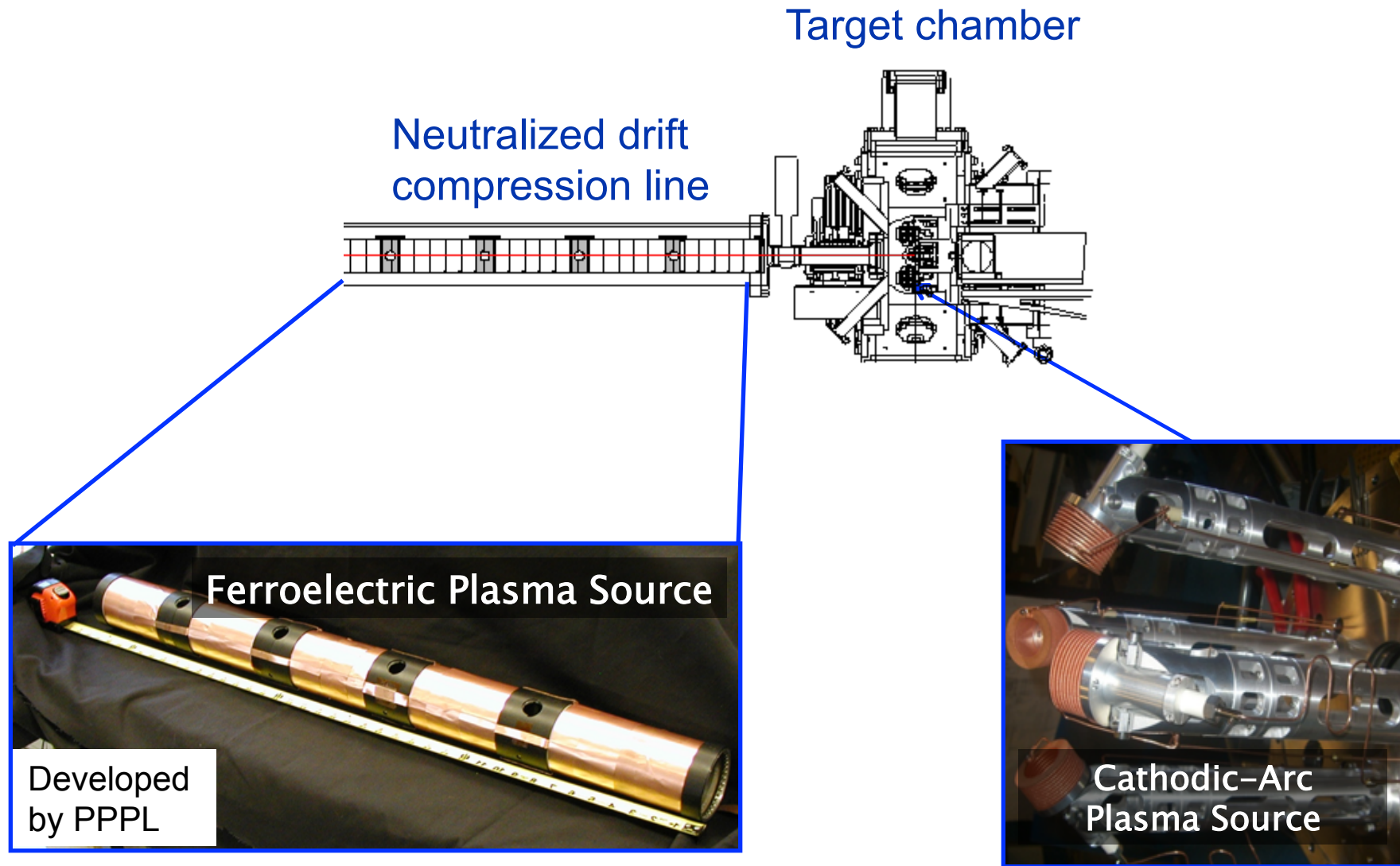*"The NDCX-II accelerator and pulsed power systems will be installed, aligned, vacuum tested, and energized with high voltage pulses. An ion beam will be accelerated and transported to a beam diagnostic station along the beam line. The beam current will be measured with a Faraday cup, and the beam profile will be recorded with 2-D scintillator images."*

Commissioning of NDCX-II is not part of the project scope. When the above criteria are met, the project will be completed.

NDCX-II plasma sources are based on NDCX-I experience

Target chamber

Neutralized drift compression line

Ferroelectric Plasma Source

Developed by PPPL

Cathodic–Arc Plasma Source

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Initially NDCX-II will reuse the same NDCX-I target chamber

GATE VALVE

TARGET MANIPULATOR AND HEXAPOD

FOUR MEEVA PLASMA INJECTORS

PARABOLIC MIRRORS AND LIGHT COLLECTION SYSTEM

ION BEAM

ION BEAM DIAGNOSTICS PADDLE

FINAL FOCUS SOLENOID

4 FRONT, 4 BACK, AND 8 RADIAL VIEWPORTS AIMED TOWARDS TARGET CENTER

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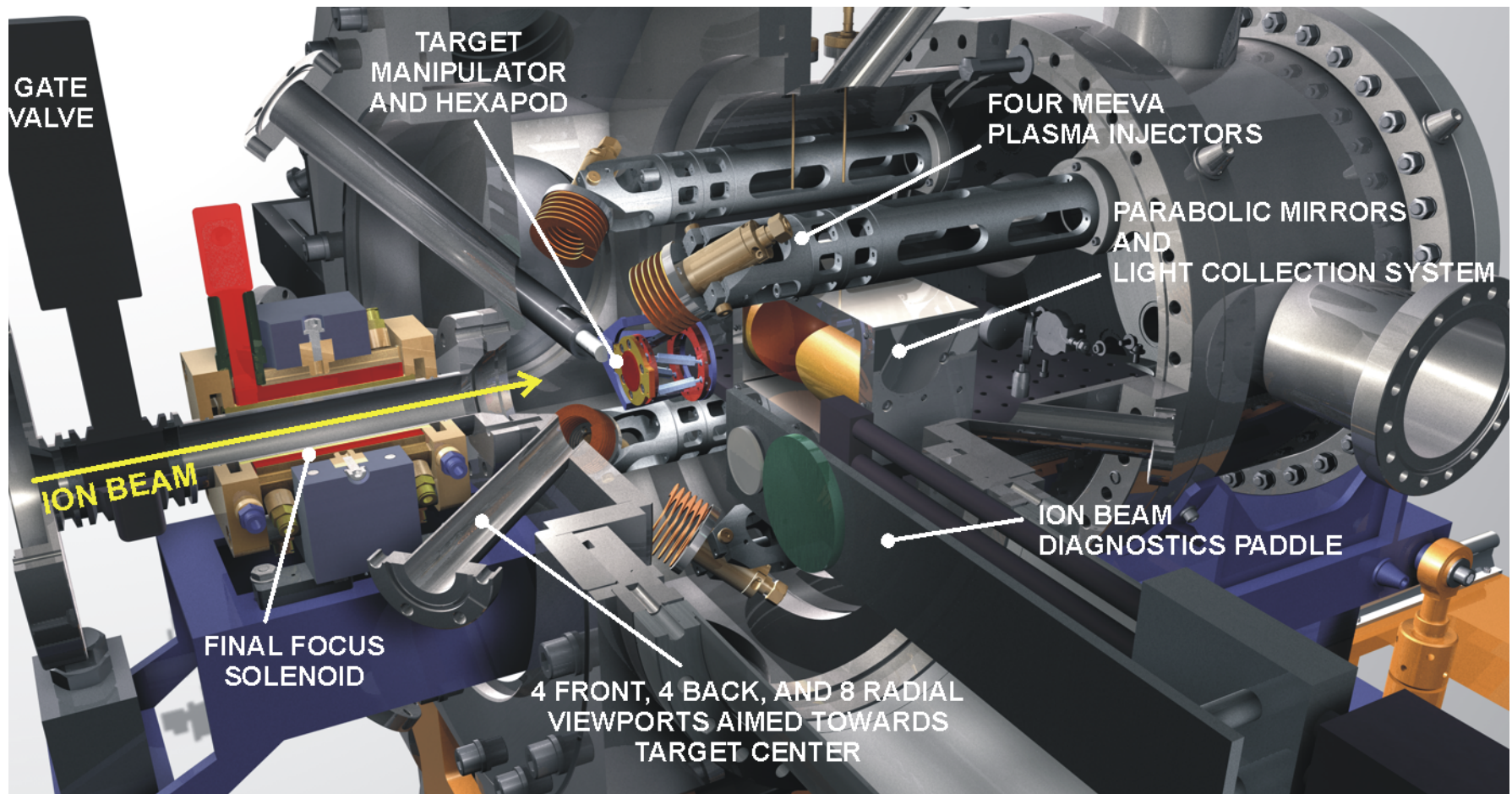
Accelerator induction cell, solenoid, magnet measurement stand
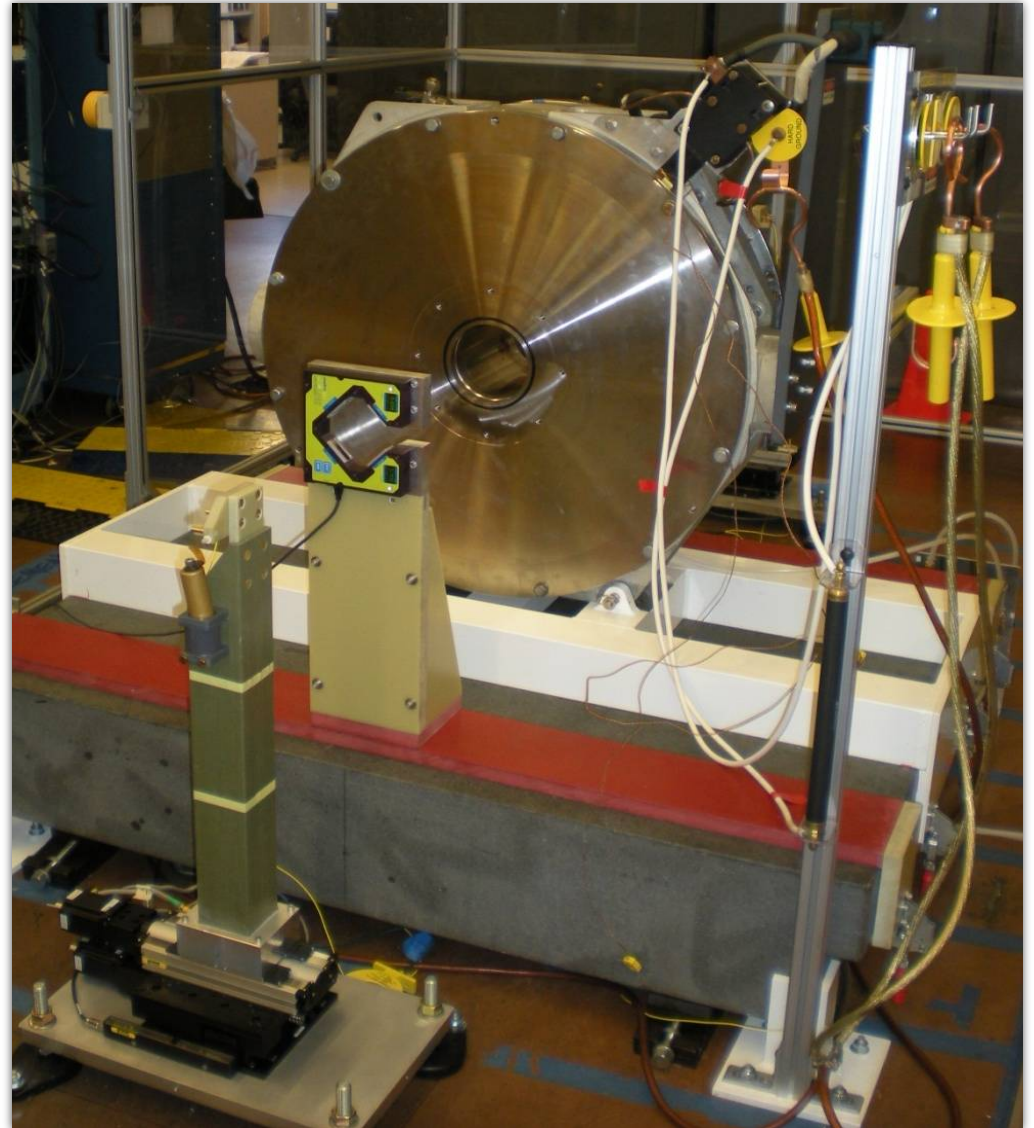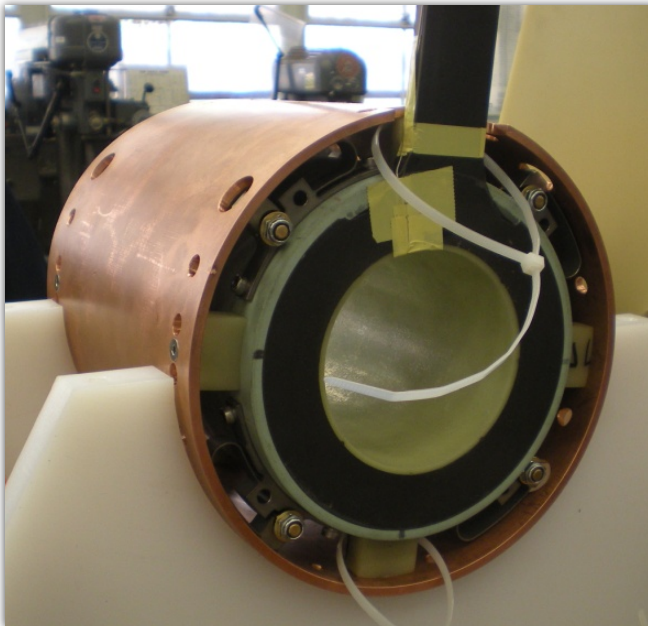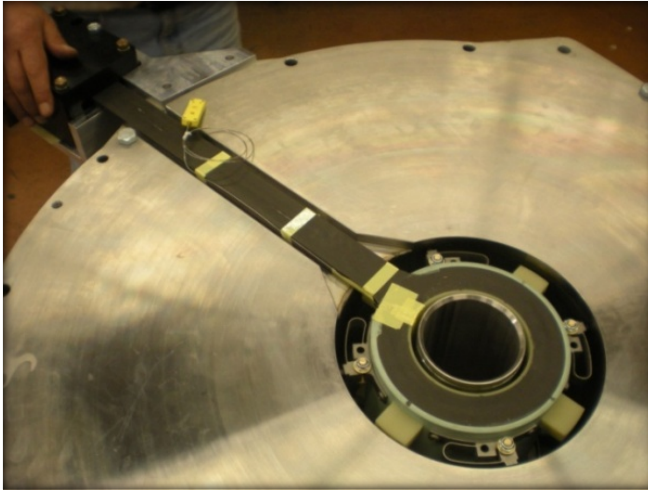
The NDCX-II test stand is used to test compression section pulsers and beam position monitors
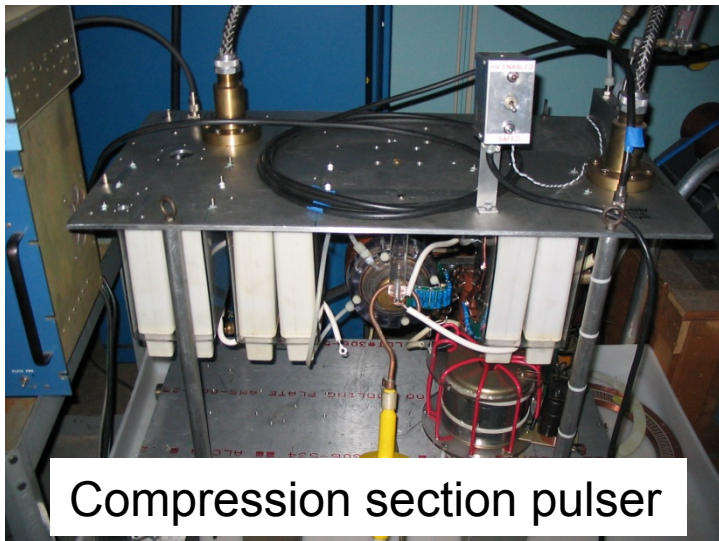
Compression section pulser
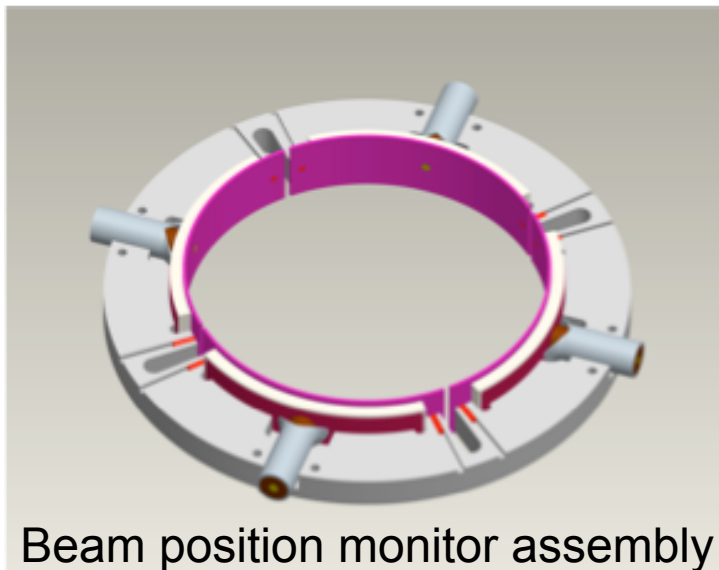
Beam position monitor assembly

NDCX-II test stand

Control Room

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The source assembly has reached full temperature and improvements continue to be made to increase the filament reliability. We now have 3 coated sources and 2 filament assemblies.

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Pulsed Power Systems

All 28 solenoid pulser racks have been fabricated and installed. Main output cables are being routed to the beam line now.

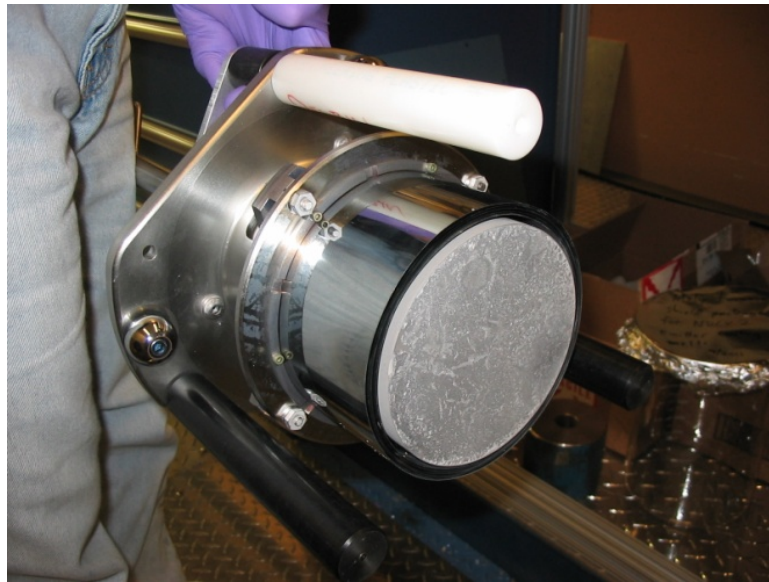The complete system for injector operation has been completed (interlocks, PLC vacuum system control, timing system, pulser system, DC power supplies, and the source filament power supply).

All 5 spark gap air control chassis have been fabricated and installed to control the pressure and flow of the air for the 13 spark gaps in the pulsed power systems.

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Pulsed Power Systems
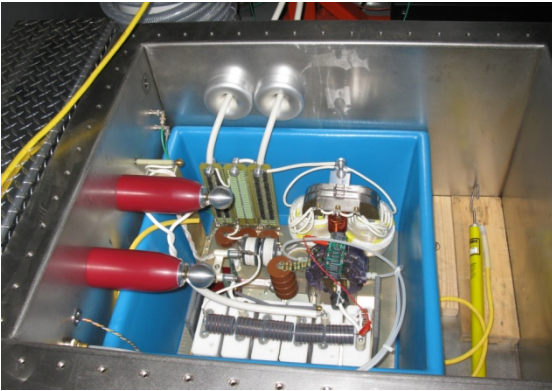
The injector pulser has been fabricated, installed, and is operational.
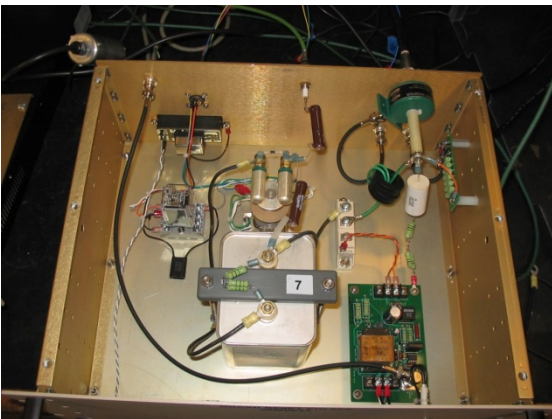
All 8 reset chassis have been fabricated and installed to reset the magnetic cores in the injector pulser and the induction cells.
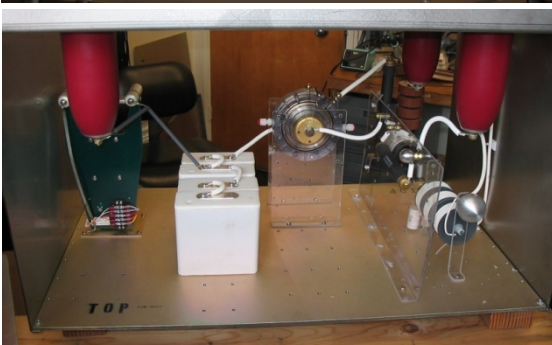
The 7 compression section pulsers are in assembly now.

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Diagnostic end station with Faraday cup, scintillator, viewports, and additional vacuum pumping

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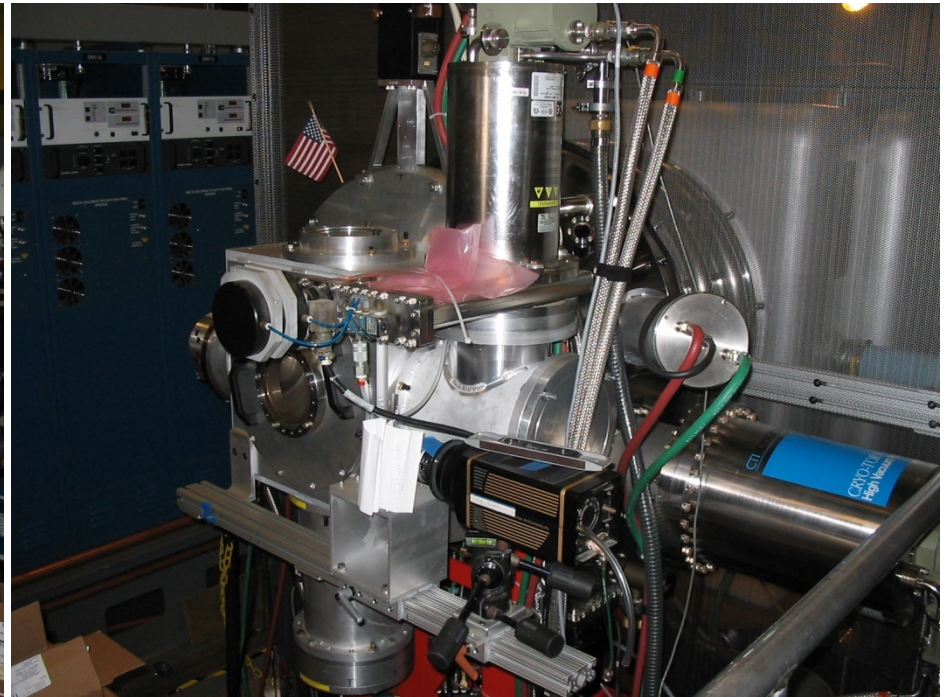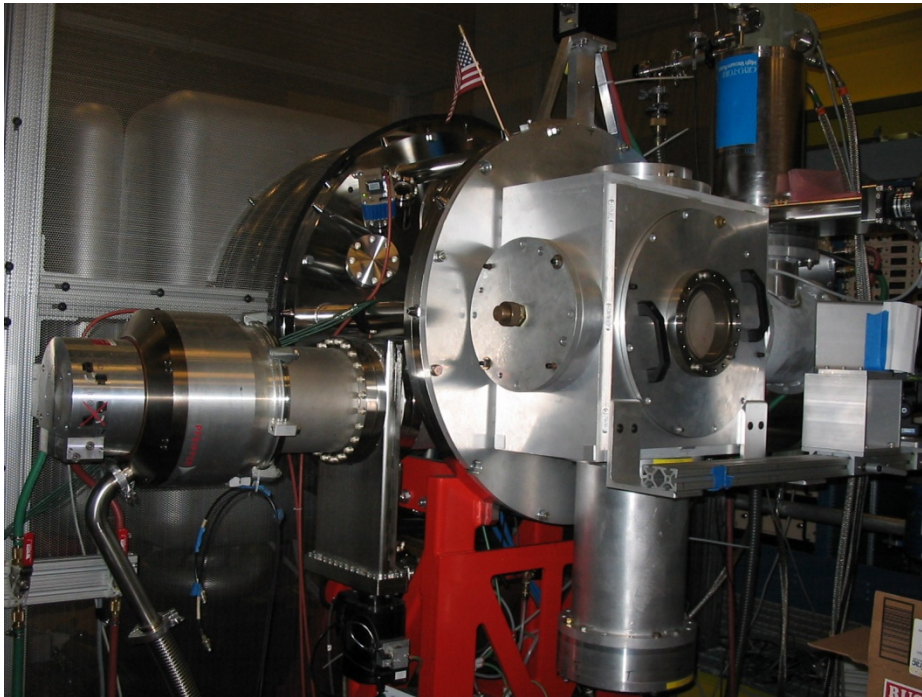
Injector and the injector pulser tank are housed within a ground cage

Diagnostic end station after the injector and 3 accelerator cells on the beamline
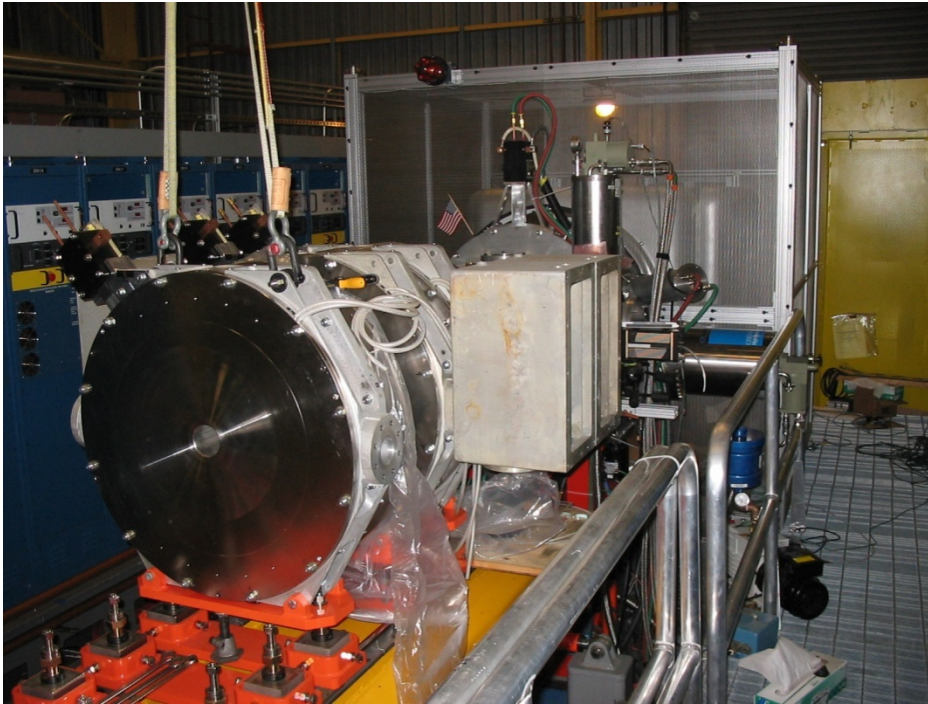
Accelerator cell and diagnostic intercell
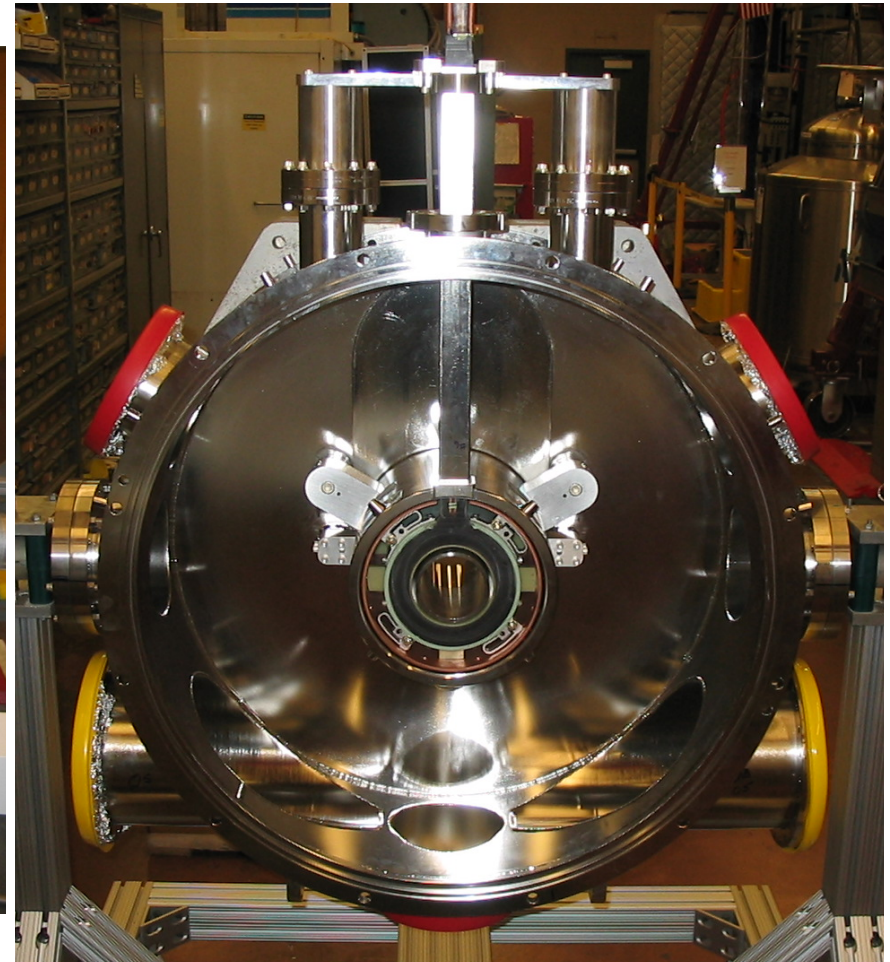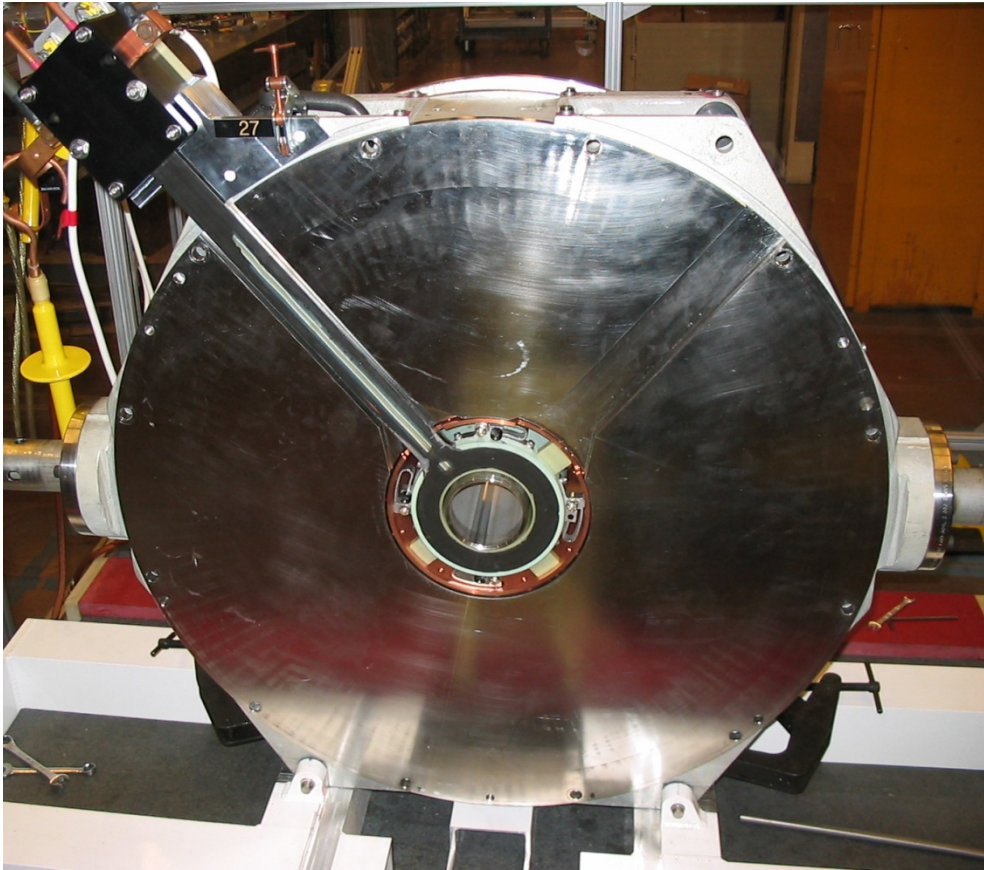
The next 4 accelerator cells are fully assembled and ready for magnet installation. The magnets have been wound and potted for these cells. The magnet for the diagnostic intercell has also been wound and potted.

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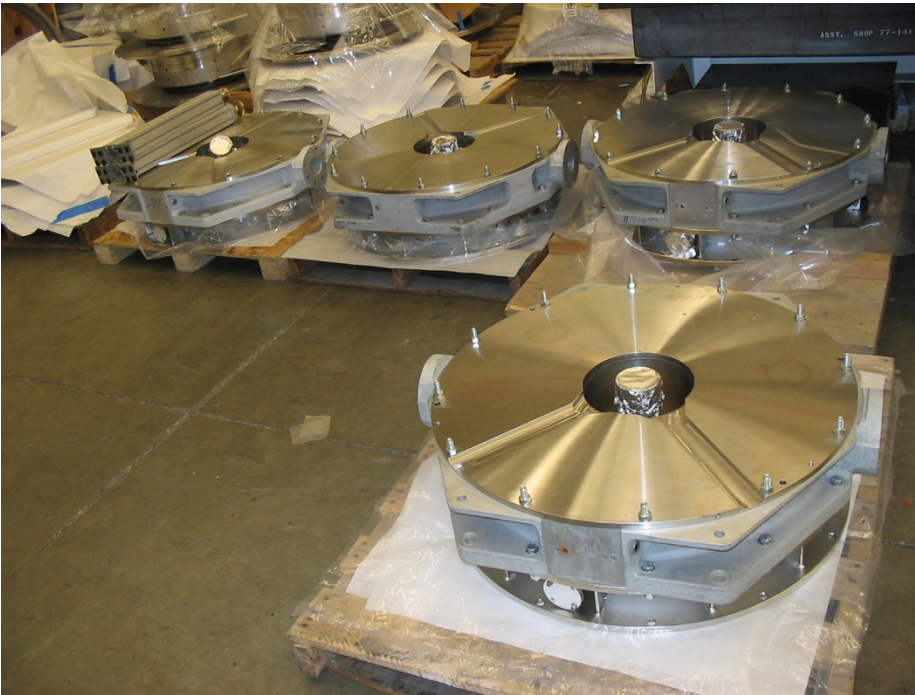
The hardware for the last 17 cells are in B77. All parts have been modified/fabricated but 11 additional solenoids will have to be wound.

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PPPL has delivered the ferroelectric plasma sources and pulsers and has completed their portion of the project deliverables
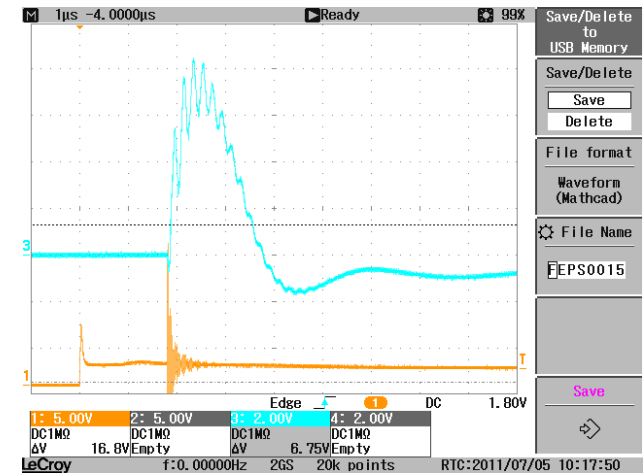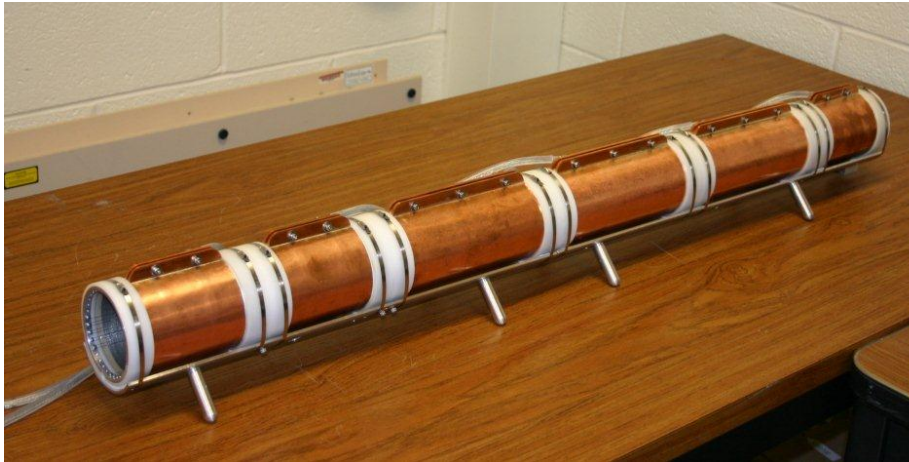
- FEPS modules have been bench tested at operating voltage and reference current waveforms have been captured for use in FEPS performance monitoring during NDCX-II operation.

- FEPS modules with HV leads have been mounted to the cradle. Modified cradle will allow mounting in the future target chamber.

- FEPS charging supplies and pulsers have been installed at LBNL.

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Beam tests have begun on the NDCX-II injector.

Pierce electrode

Extractor electrode

Acceleration Electrode

Emitter

Focusing solenoid

2.835

6.625

Movable diagnostic station
Diagnostic plane ~90cm from emitter surface
- Faraday cup
- Optical scintillator and fast, gated camera

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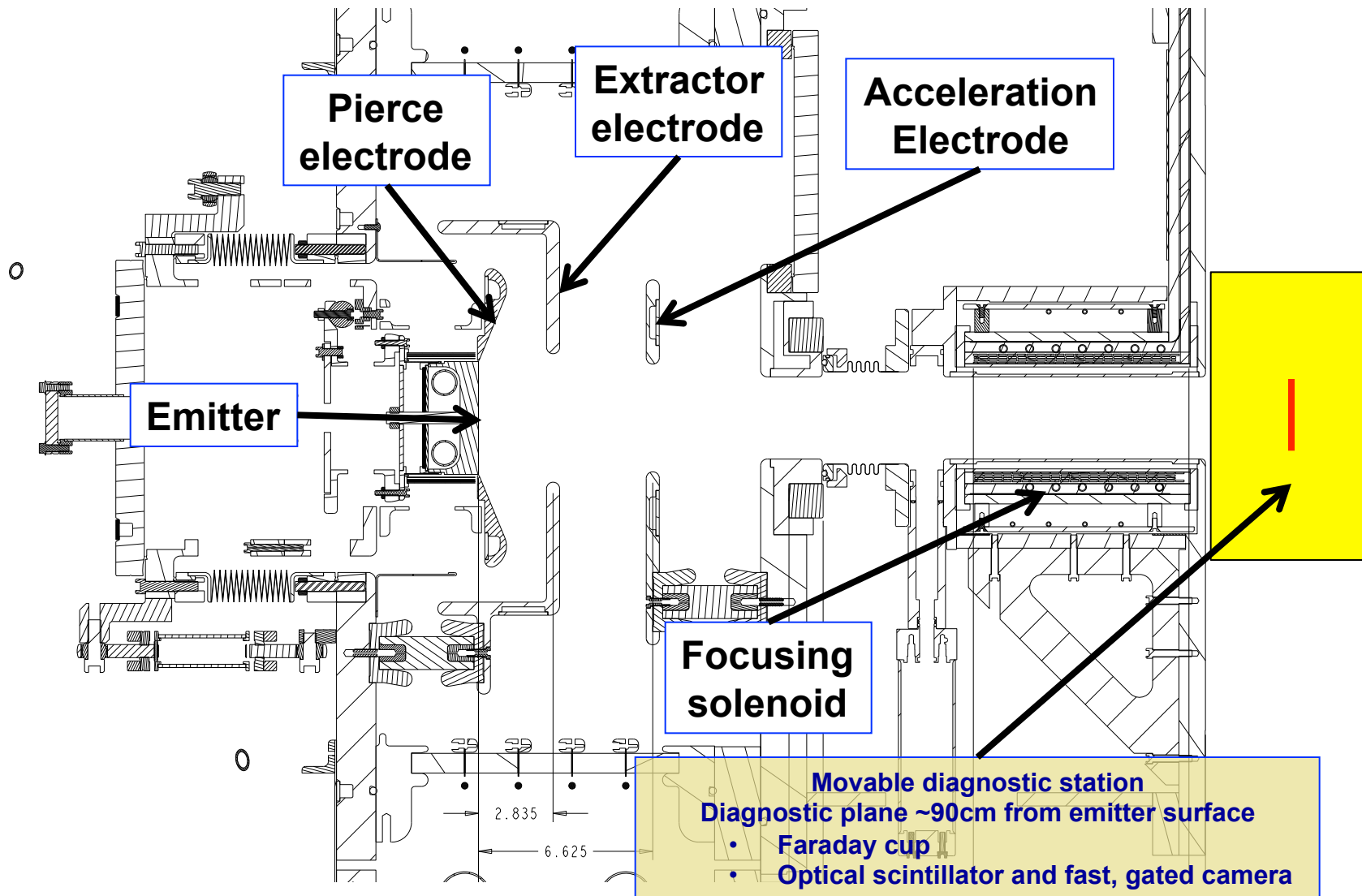
We have measured the dependence of emitted beam current on temperature and voltage.

10.9 cm diameter Li-alumino-silicate source

Legend:
- 1275 C
- 1250 C
- 1230 C
- 1210 C
- 1175 C

X-axis: Scaled extraction voltage (kV/100)3/2
Y-axis: Li Beam current (mA)

Goal:
- Ideal space-charge limited emission
- Measured current

Time (µs)
Current (mA)
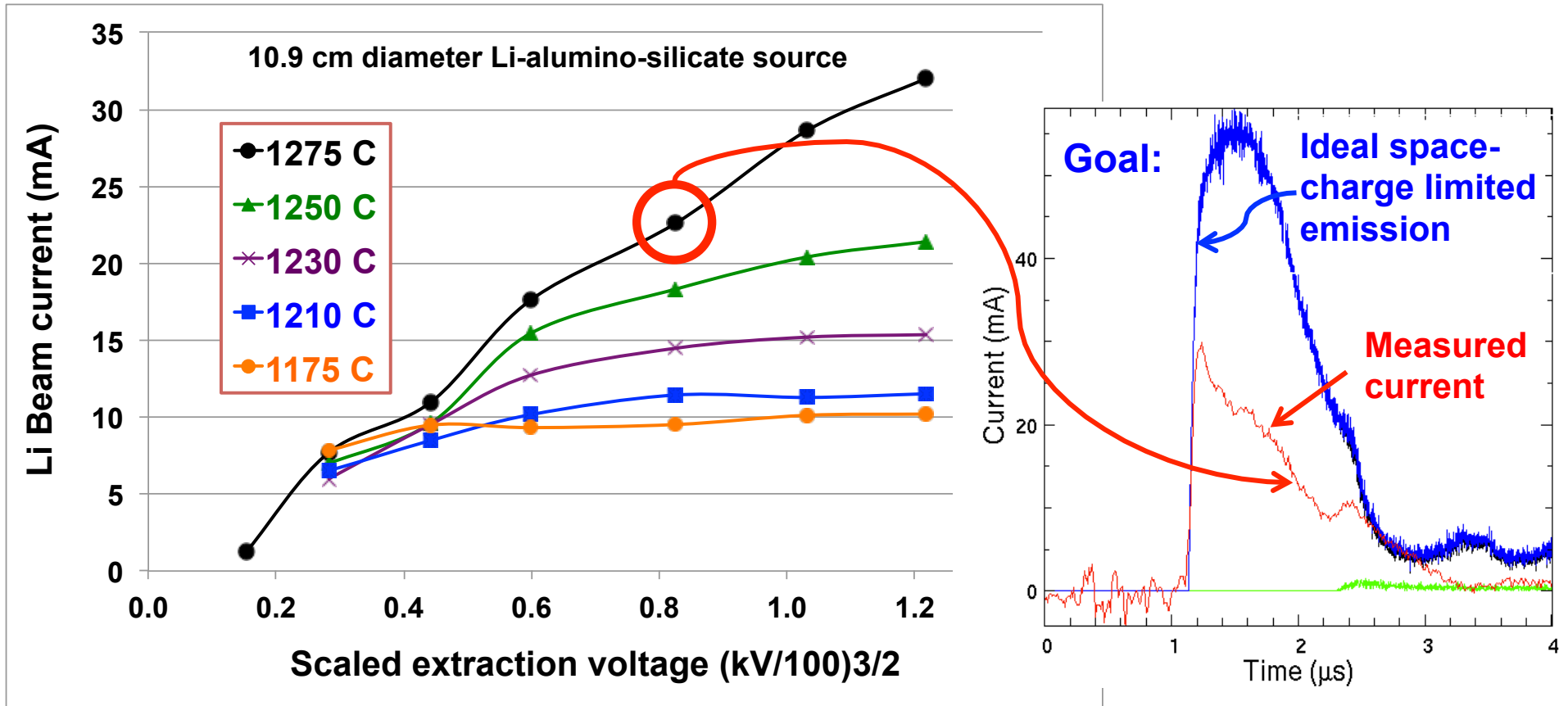
Based on previous source development experience, we expect to reach ~90 mA (at 130 kV) after the ion source is fully conditioned.

Beam images show evolution from temperature-independent to emission-limited flow.

Scintillator images obtained at downstream diagnostic station.
500ns camera gate captures the main body of the Li beam only.

27 kV   73 kV   86 kV   100 kV

Temperature-independent   Emission-limited

2.5 cm   2.5 cm   2.5 cm   2.5 cm
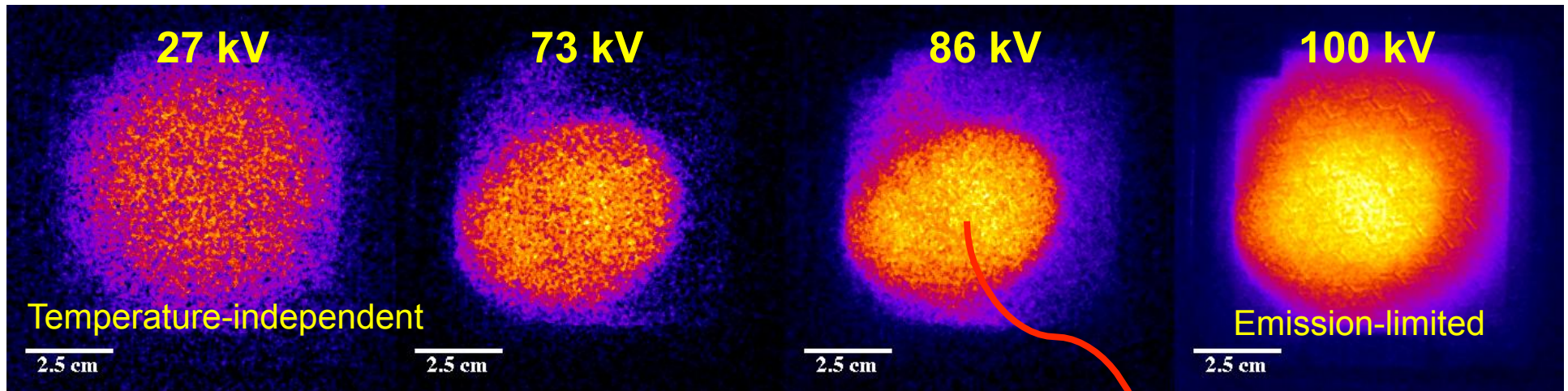
Ion source brightness temperature at 1250 C

Beam spatial uniformity confirms uniform emission from source.

FWHM ~6cm

Beam spot size matches simulations.

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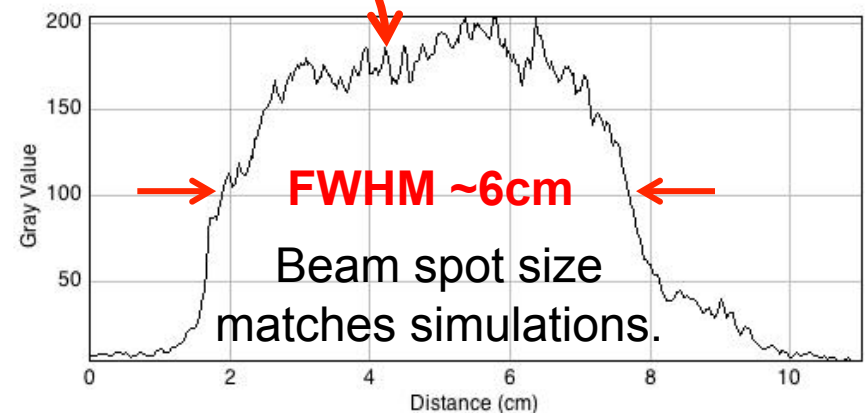
WARP modeling explains departure from temperature-independent emission with a thermionic emission model.

Measured

Measured + WARP

Li+

Time-delayed impurity
(K+ , deduced from time-of-flight)

1275 C
88kV

Li   (95%)
K   (5%)
Li+K
Measured
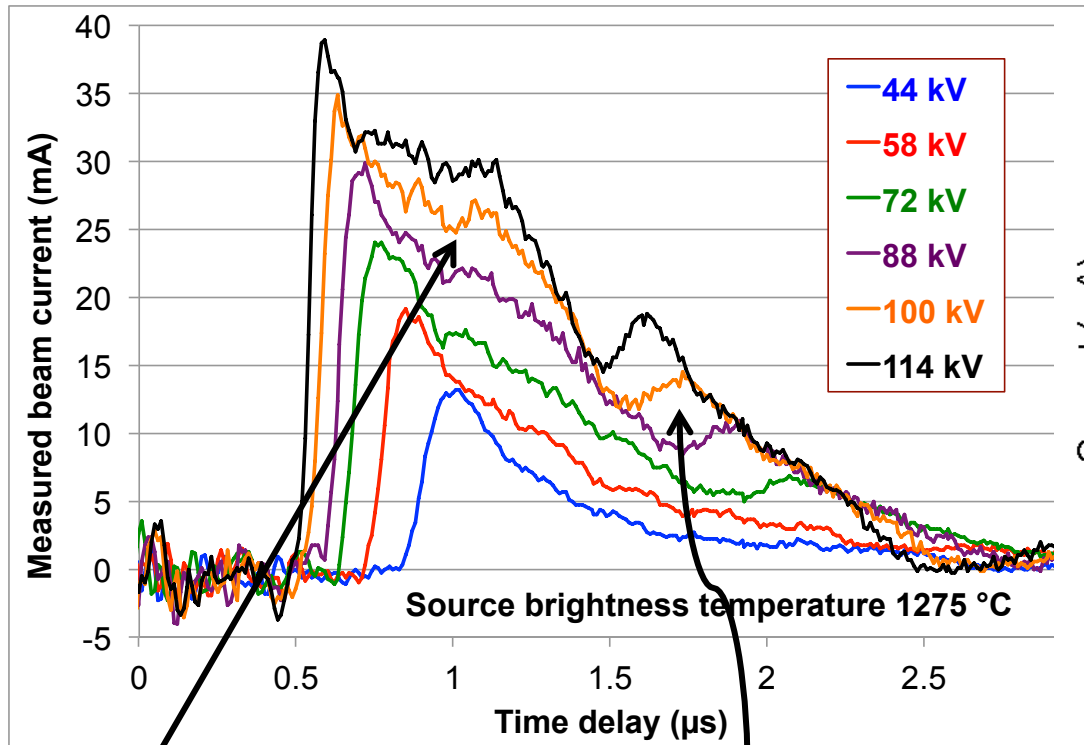
Experimentally, the impurity emission is observed to decrease with conditioning time.

All planned milestones have been met so far

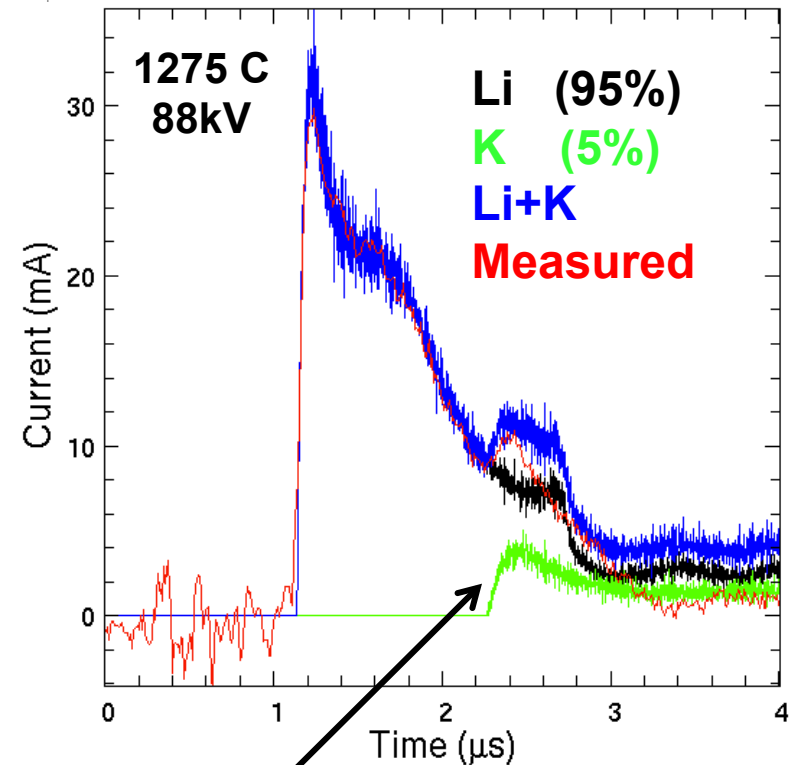| Milestones	Planned	Achieved
Complete NEPA Review/Issue Record of Decision	Jul-09	**Jul-09**
Recovery Act Funds Distribution	Jul-09	**Jul-09**
Begin Prototype and Refurbishment Activities	Aug-09	**Aug-09**
Complete detailed engineering design of prototype test cell. Begin equipment procurement.	Sep-09	**Sep-09**
Establish project Baseline Plan	Dec-09	**Dec-09**
Conduct Technical Baseline and Management Review, Continue equipment procurement of accelerator components	Mar-10	**Mar-10**
Complete Pulsed Power Prototypes (Cell and Magnet Pulsers)	Jun-10	**Jun-10**
Complete First Article Induction Cell	Sep-10	**Sep-10**
Complete Accelerator Equipment Platform Installation	Dec-10	**Aug-10**
Complete Injector Design	Mar-11	**Dec-10**
Complete Accelerator Cell Refurbishment	Jun-11	**Feb-11**
Complete Injector Fabrication	Sep-11	**Aug-11**
Complete Accelerator Installation	Dec-11	
NDCX-II Beam Accelerated, Project Complete	Mar-12	

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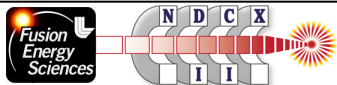
Summary

- We have successfully run the ion source at full temperature and operated the injector as a system.

- We will complete the CD-4 requirements within the next few weeks and continue assembling and installing additional cells until projects funds are depleted.

- The final assembly and installation of the remaining 17 cells will continue on HIF program funds until March to complete the original 27-cell configuration according to the Project Execution Plan.

- The project is within schedule but has an estimated cost overrun of ~ 4.5%.

- Lessons Learned

  - Non-performing vendors

  - Management changes

  - Optimistic cost estimates and unexpected technical difficulties

  - Outside contractors performing work onsite

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Target Chamber Procurement Status

- Request for proposals were sent out to 5 vendors

- Proposals are due on 10/27/11

- Waiting for the drawing package, mechanical analysis, and vendor experience from LANL

- After receiving drawing package from LANL, 1 week is needed for minor drawing package modifications

- Modified drawing package will go back to the vendors for revised proposals

- Goal is to order the chamber by the end of November

- Existing funding of 825k$ is expected to only cover the chamber procurement

- Additional funding will be required to start engineering of components inside the target chamber and procure diagnostic equipment

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"Tuning V" algorithm (modeled in ASP) adjusts "steering" dipole currents so as to minimize a penalty function at the next sensor

x,y vs z trajectories of head, mid, tail particles and the corkscrew size for a typical ASP run
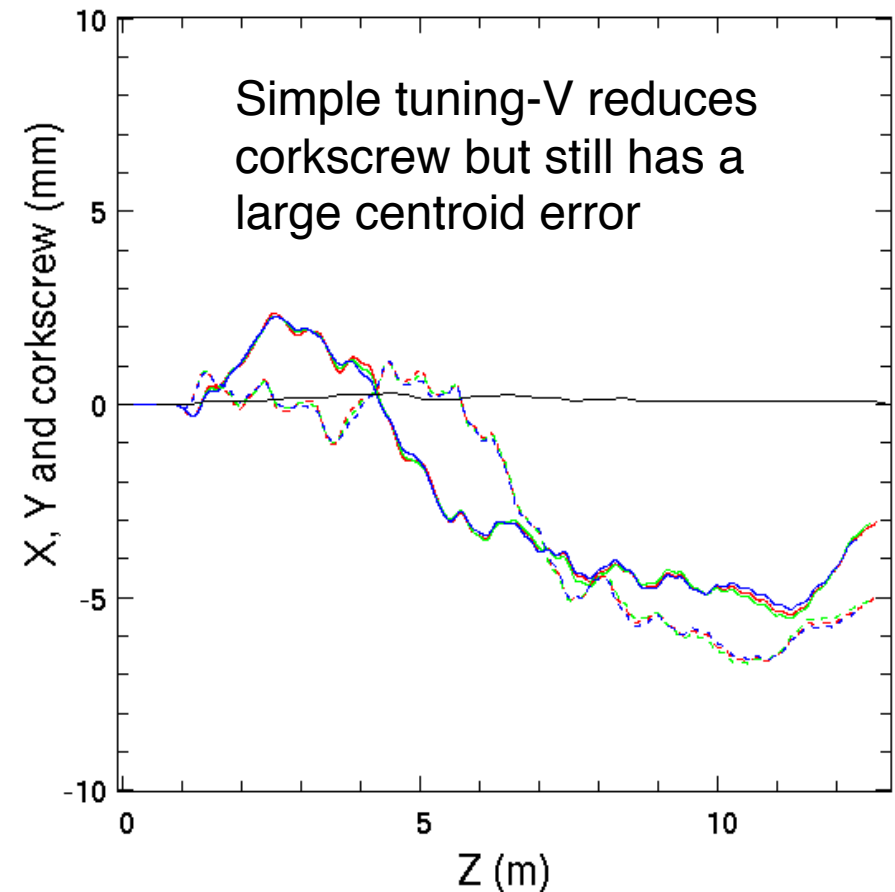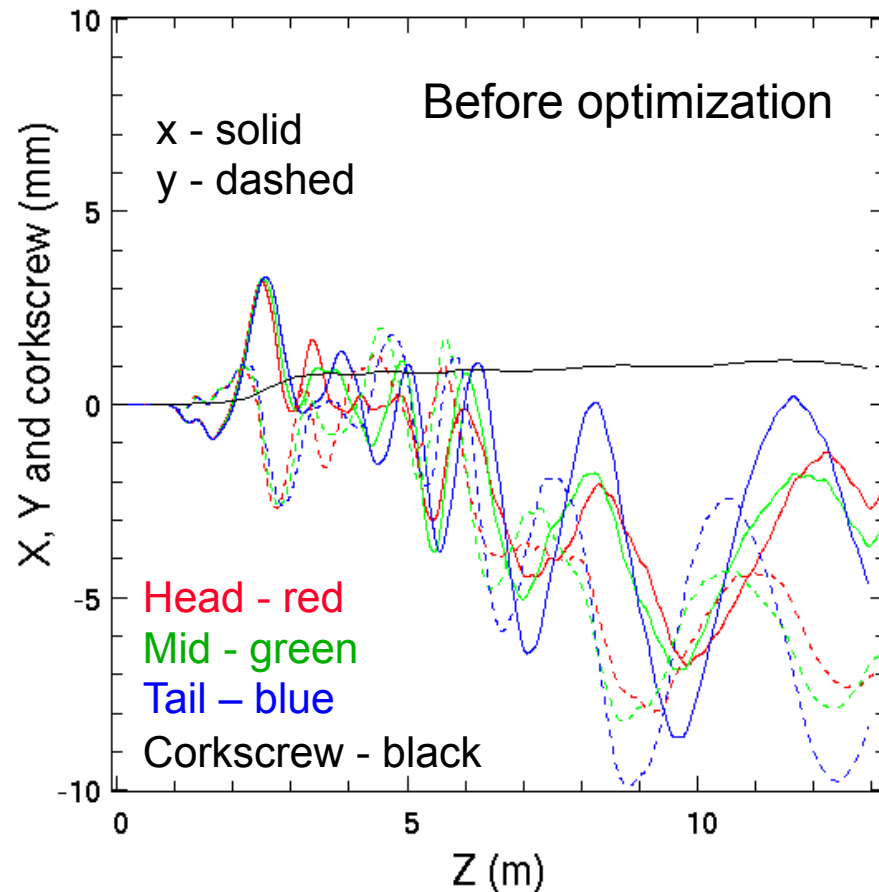
Random offsets of solenoid ends up to 1 mm were assumed; the effect is linear.

Beam offset can be added to penalty, but care is needed

Resonance occurs between sensor spacing and centroid oscillation
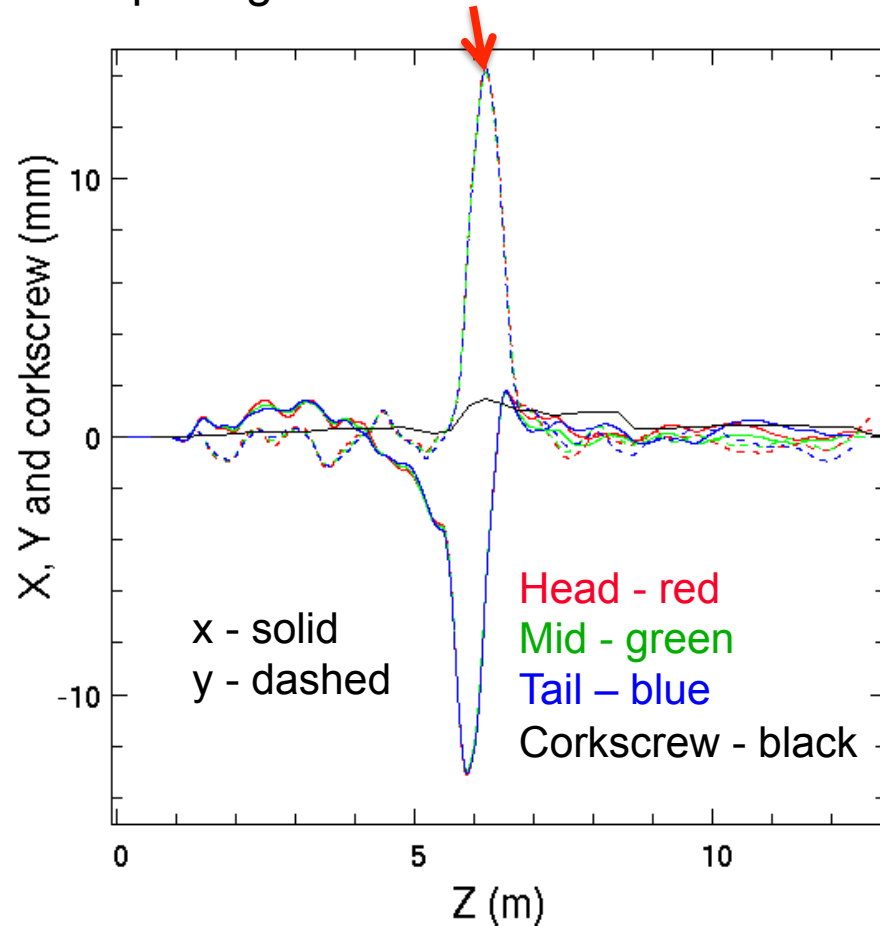
Constraining the dipole strength to < 100 Gauss reduces the peak

x - solid
y - dashed

Head - red
Mid - green
Tail – blue
Corkscrew - black

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An ensemble of runs shows the same trends

x,y vs z trajectories of head, mid, tail particles and the corkscrew amplitude
Before optimization

Head - red
Mid - green
Tail – blue
Corkscrew - black
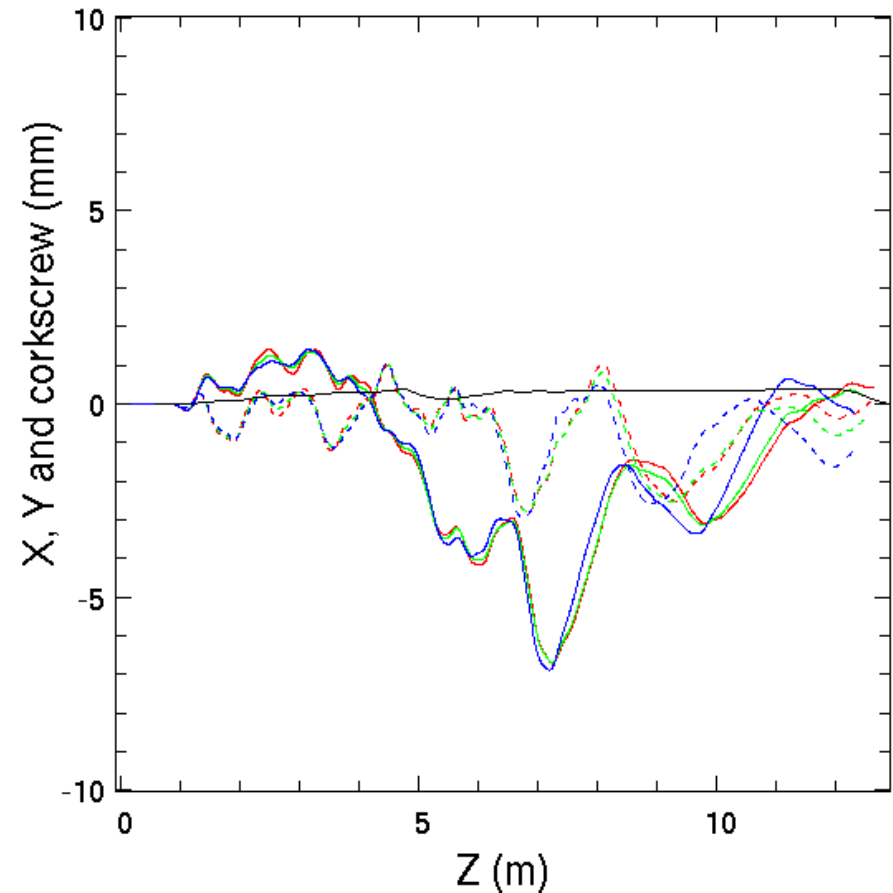
x - solid
y - dashed

Simple tuning-V algorithm reduces the corkscrew amplitude but does not reduce the centroid error
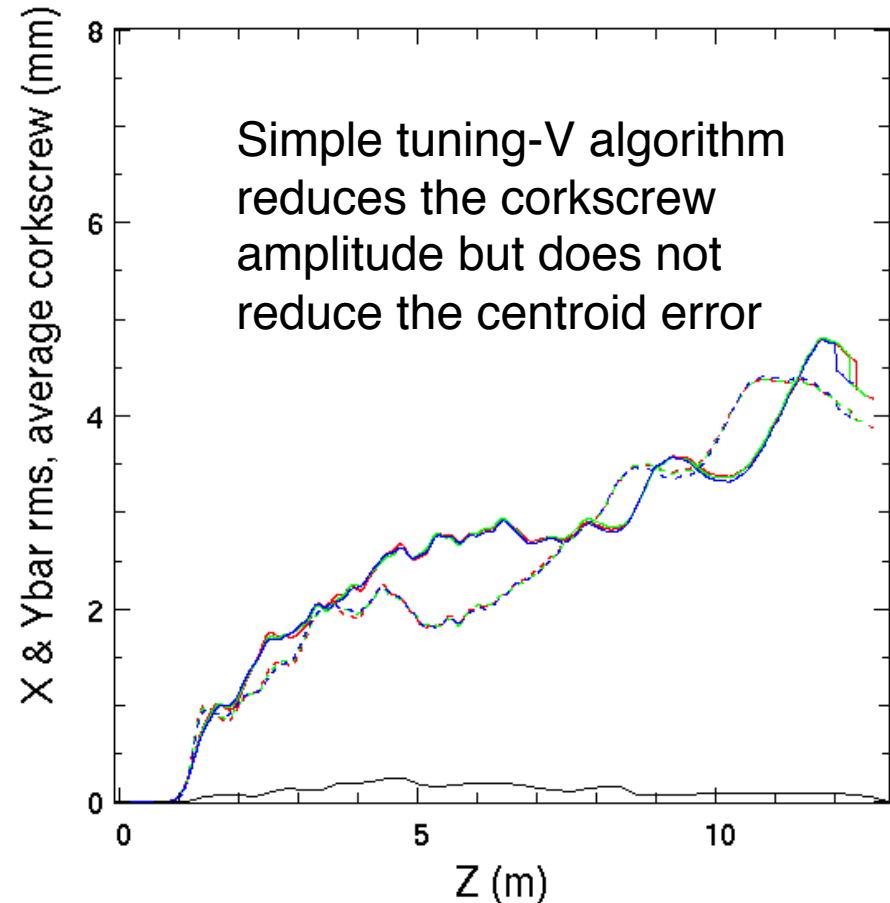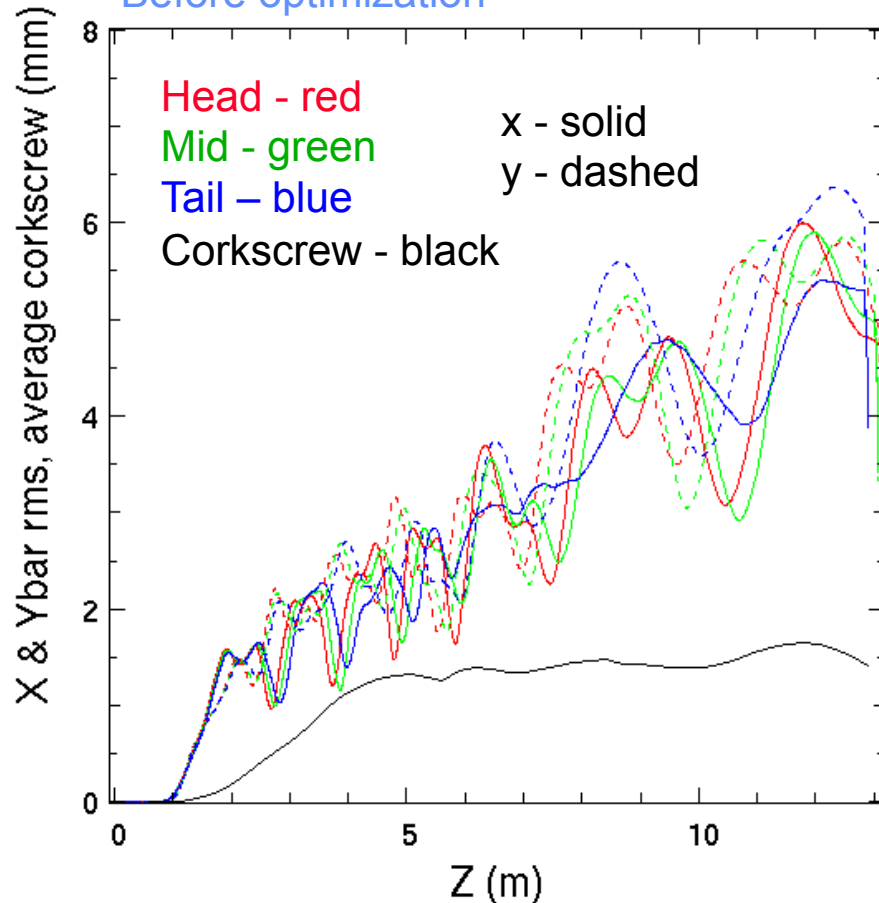
The results are averages over 20 simulations with differing random offsets of solenoid ends up to 1 mm.

The effects of penalizing the beam offset and dipole strength are clearer when an ensemble of runs is examined

Resonance between sensor spacing and cyclotron oscillation spatial period
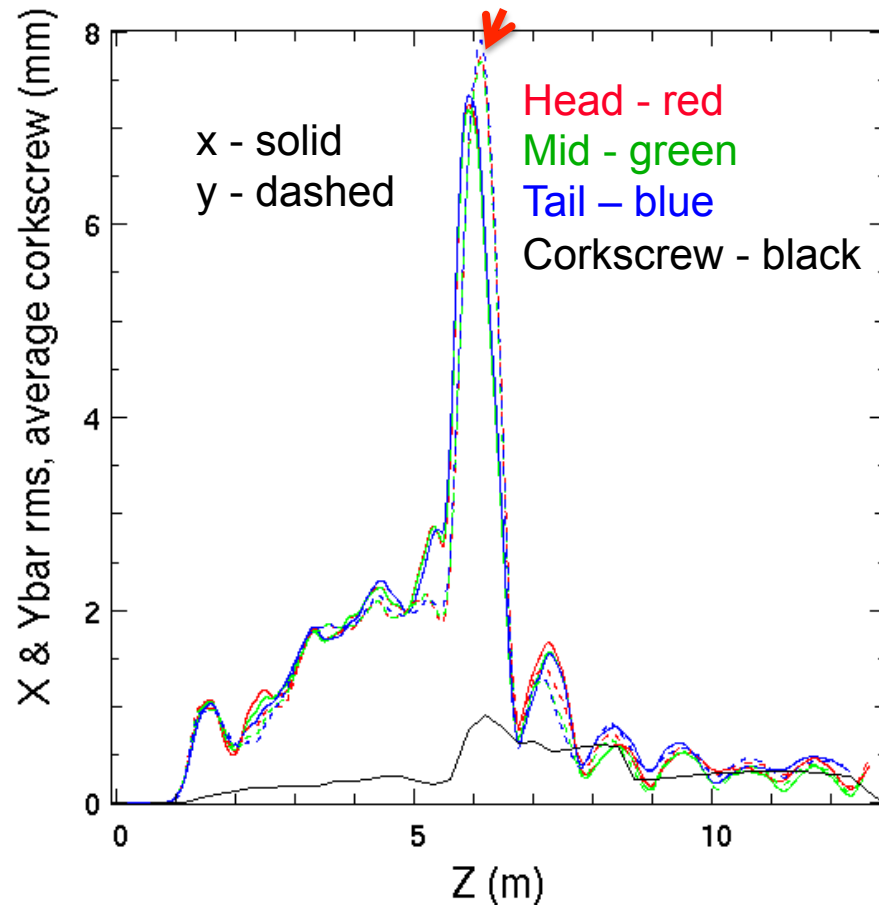
Constraining the dipole strength to < 100 Gauss removes the peak

x - solid
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Head - red
Mid - green
Tail – blue
Corkscrew - black

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EXTRAS – ASP code

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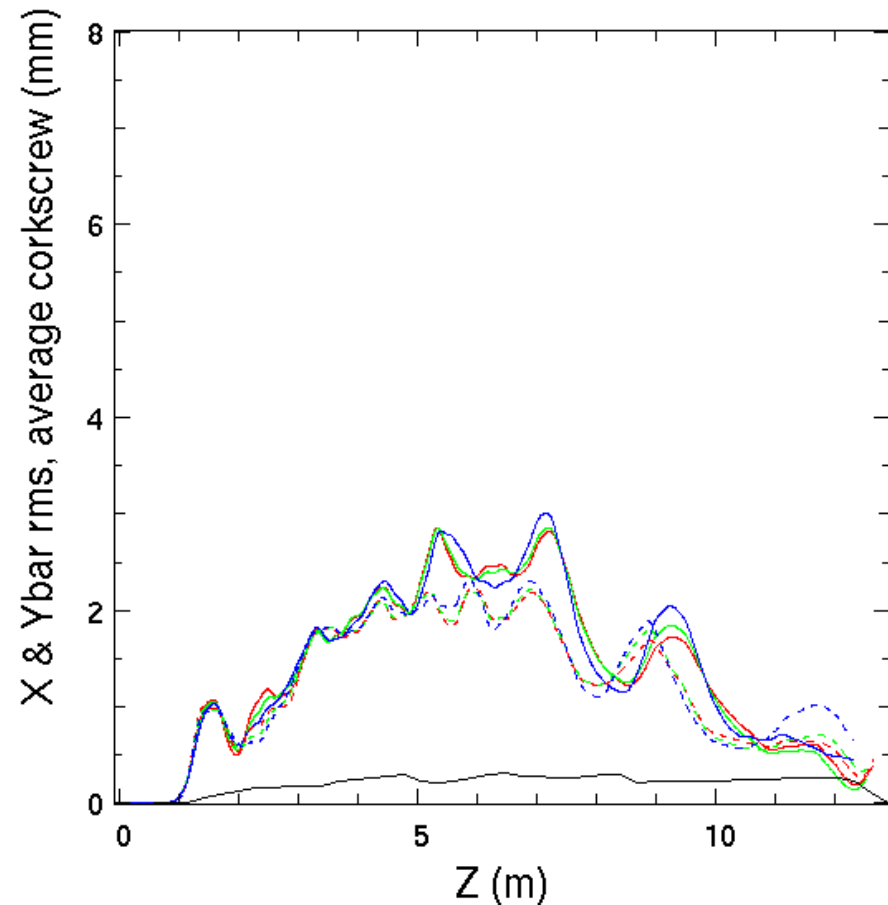
1-D PIC code ASP ("Acceleration Schedule Program")

- Follows (z, v_z) phase space using a few hundred particles ("slices")
- Accumulates line charge density $\lambda(z)$ on a grid via particle-in-cell
- Space-charge field via Poisson equation with finite-radius correction term

$$\frac{\partial^2 \phi(z)}{\partial z^2} - k_\perp^2 \phi(z) = -\frac{\lambda(z)}{\epsilon_0 \pi r_{\text{beam}}^2} \; ; \qquad E_z(z) = -\frac{\partial \phi(z)}{\partial z}$$

$$k_\perp^2 = \frac{4}{g_0 r_{\text{beam}}^2} \; ; \qquad g_0 = 2 \ln \frac{r_{\text{wall}}}{r_{\text{beam}}} + \alpha$$

  Here, α is between 0 (incompressible beam) and ½ (constant radius beam)

- Acceleration gaps with longitudinally-extended fringing field
  - Idealized waveforms
  - Circuit models including passive elements in "comp boxes"
  - Measured waveforms
- Centroid tracking for studying misalignment effects, steering
- Optimization loops for waveforms & timings, dipole strengths (steering)
- Interactive (Python language with Fortran for intensive parts)

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The field model in ASP yields the correct long-wavelength limit

- For hard-edged beam of radius r_b in pipe of radius r_w, 1-D (radial) Poisson eqn gives:

$$\phi(r) = \frac{\lambda}{2\pi\epsilon_0} \left\{ \begin{array}{ll} \left[\frac{1}{2}\left(1 - \frac{r^2}{r_b^2}\right) + \ln\frac{r_w}{r_b}\right], & r < r_b \\ \ln\left(\frac{r_w}{r}\right), & r_b \leq r < r_w \end{array} \right.$$

- The axial electric field within the beam is:

$$E_z(r,z) = -\frac{1}{2\pi\epsilon_0} \left\{ \left[\frac{1}{2}\left(1 - \frac{r^2}{r_b^2}\right) + \ln\frac{r_w}{r_b}\right] \frac{\partial\lambda(z)}{\partial z} - \left[1 - \frac{r^2}{r_b^2}\right] \frac{\lambda(z)}{r_b} \frac{\partial r_b}{\partial z} \right\}$$

- For a space-charge-dominated beam in a uniform transport line, $\lambda/r_b^2 \approx$ const.; find:

$$E_z(r,z) = -\frac{g_{\text{scd}}}{4\pi\epsilon_0} \frac{\partial\lambda(z)}{\partial z}; \qquad g_{\text{scd}} = 2\ln\frac{r_w}{r_b}$$

- For an emittance-dominated beam $r_b \approx$ const.; average over beam cross-section, find:

$$\langle E_z\rangle(z) = -\frac{g_{\text{ed}}}{4\pi\epsilon_0} \frac{\partial\lambda(z)}{\partial z}; \qquad g_{\text{ed}} = 2\ln\frac{r_w}{r_b} + \frac{1}{2}$$

- The ASP field equation limits to such a "g-factor" model when the $k_\perp^2$ term dominates
- In NDCX-II we have a space-charge-dominated beam, but we adjust the solenoid strengths to keep r_b more nearly constant; $\quad g_0 = 2\ln(r_w/r_b) + \alpha; \quad 0 < \alpha < 1/2$
- In practice we tune α to obtain agreement with Warp results

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A "zero-dimensional" Python code (essentially, a spreadsheet) captures the essence of the NDCX-II acceleration schedule

- Computes energy jumps of nominal head and tail particles at gaps
- Space-charge-induced energy increments between gaps via a "g-factor" model
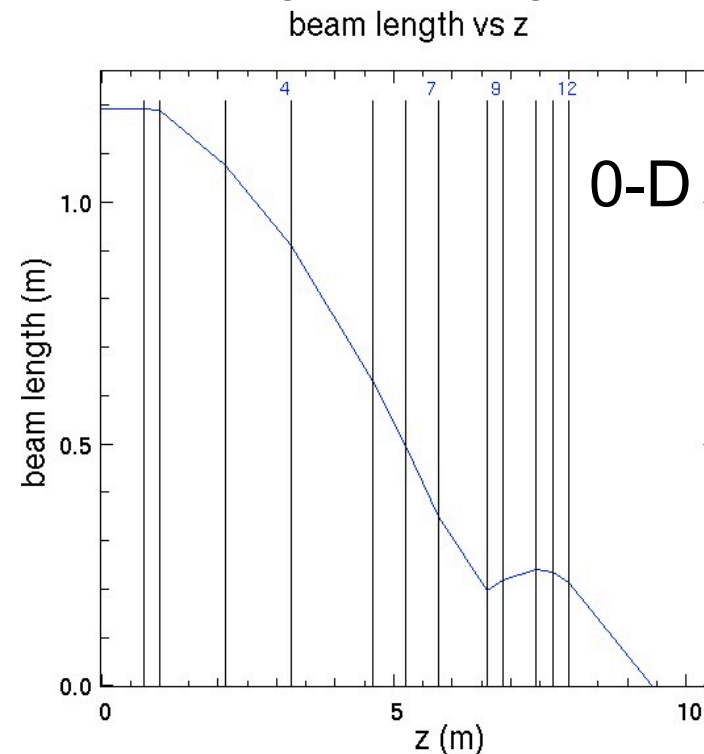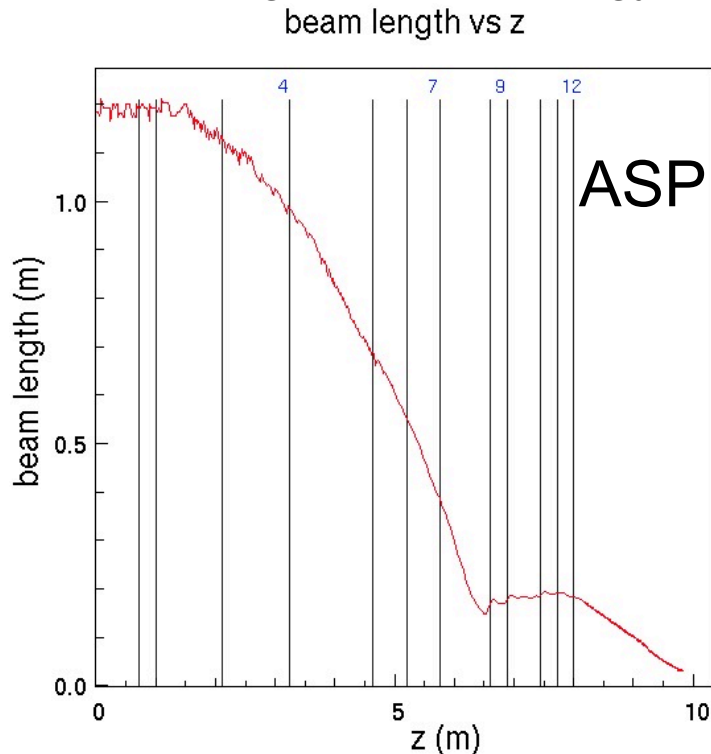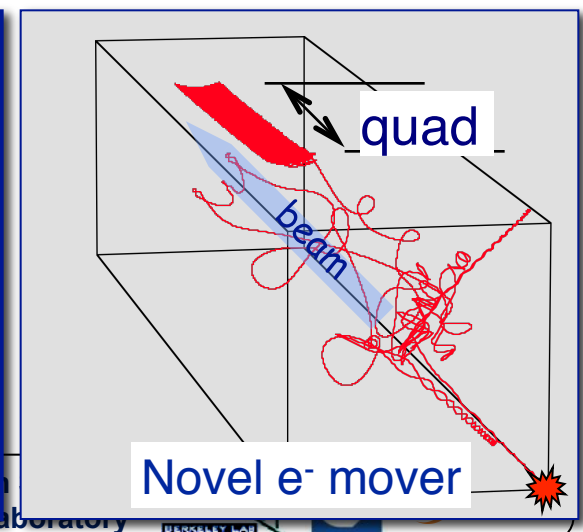

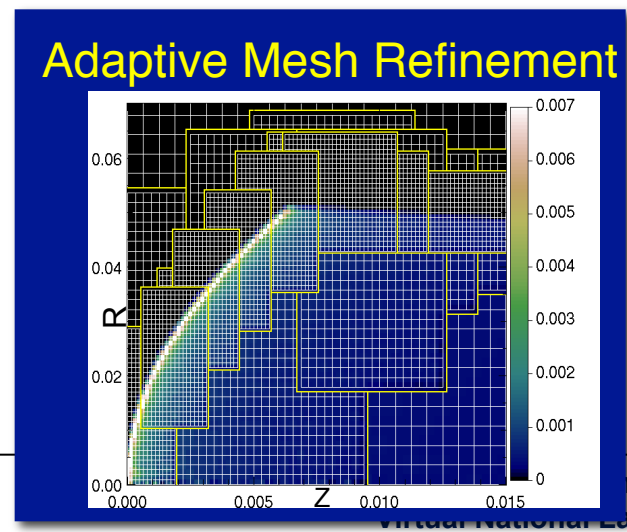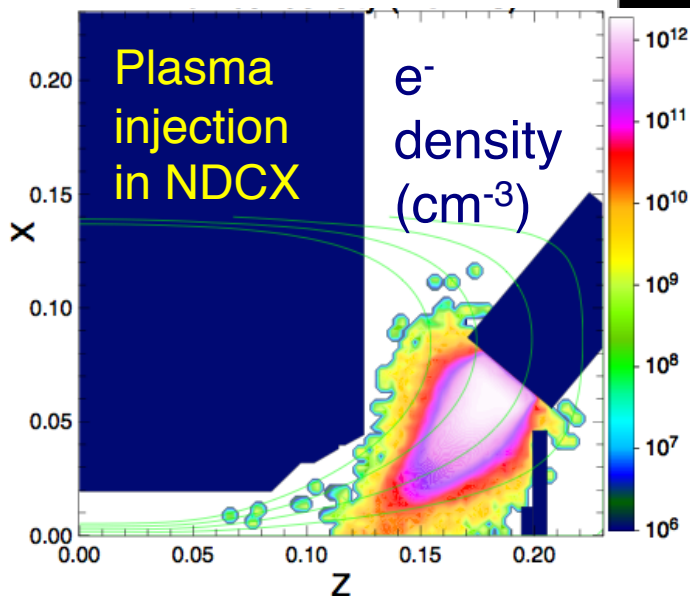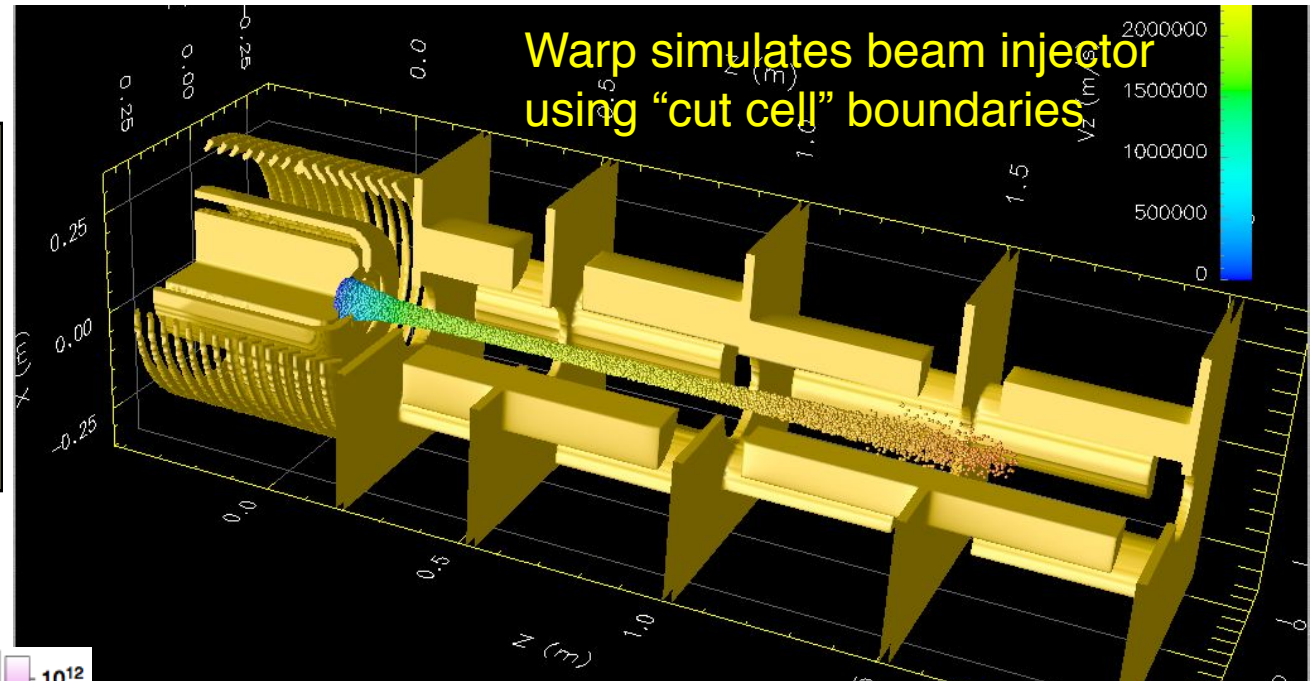- The final head and tail energies (keV) are off; the g-factor model does not accurately push the head and tail outward:

	0-D	ASP
head	923	1100
tail	1082	1300

- But – not bad, for a main loop of 16 lines.

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EXTRAS – Warp code

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The HIF program has developed advanced methods to enable efficient simulation of beam and plasma systems

With new electron mover and mesh refinement, run time in an electron cloud problem was reduced from 3 processor-months to 3 processor-days

Warp simulates beam injector using "cut cell" boundaries

Plasma injection in NDCX

e⁻ density (cm⁻³)

Adaptive Mesh Refinement
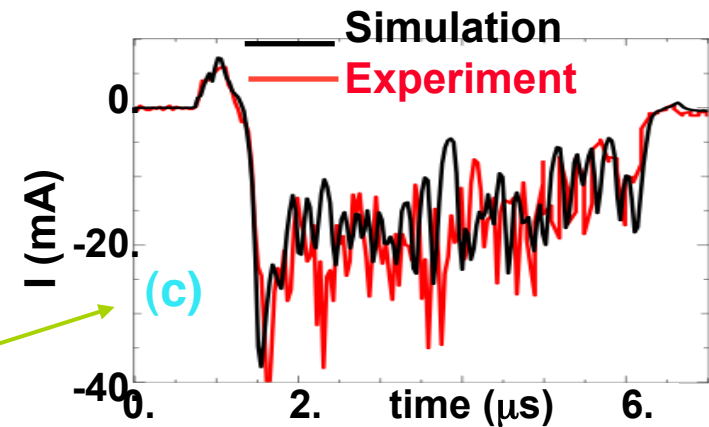
quad

beam

Novel e⁻ mover

Warp

- **Warp is a state-of-the-art 3-D parallel multi-physics code and framework**
  - *modeling of beams in accelerators, plasmas, laser-plasma systems, non-neutral plasma traps, sources, etc.*
  - *unique features: ES/EM solvers, cut-cells, AMR, particles pushers, python interface, etc.*

- **Contribution to projects**
  - **HIFS-VNL (LBNL,LLNL,PPPL)**: work-horse code; design and support expts.
  - **VENUS ion source (LBNL)**: modeling of beam transport
  - **LOASIS (LBNL)**: modeling of LWFA in a boosted frame
  - **FEL/CSR (LBNL)** : modeling of free e- lasers & coherent synch. radiation in boosted frame
  - **Anti H- trap (LBNL/U. Berkeley)**: simulation of model of anti H- trap
  - **U. Maryland**: modeling of UMER sources and beam transport; teaching
  - **Ferroelectric plasma source (Technion, U. Maryland)**: modeling of source
  - **Fast ignition (LLNL)**: modeling physics of filamentation
  - **E-cloud for HEP (LHC, SPS, ILC, Cesr-TA, FNAL-MI)**: see slide on Warp-Posinst
  - **Laser Isotope Separation (LLNL)**: now defunct
  - **PLIA (CU Hong Kong)**: modeling of beam transport in pulsed line ion accelerator
  - **Laser driven ions source (TU Darmstadt)**: modeling of source

- **Benchmarking**
  - Heavily benchmarked against various experiments: MBE4, ESQ ion source, HCX, multibeamlet ion source, UMER, NDCXI, etc.; codes: IGUN, LSP; theory: beam transport and plasma analytic theory

88

The Warp code includes e-cloud & gas models; here, we modeled and tested deliberate e-cloud generation on HCX
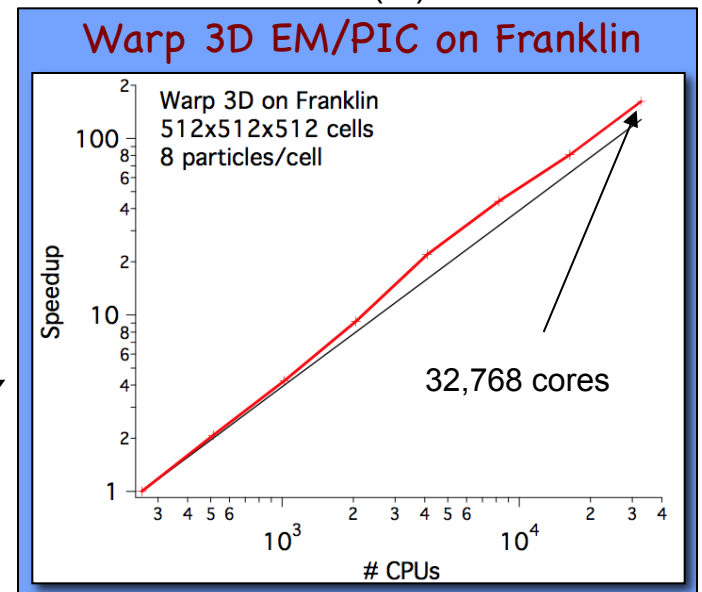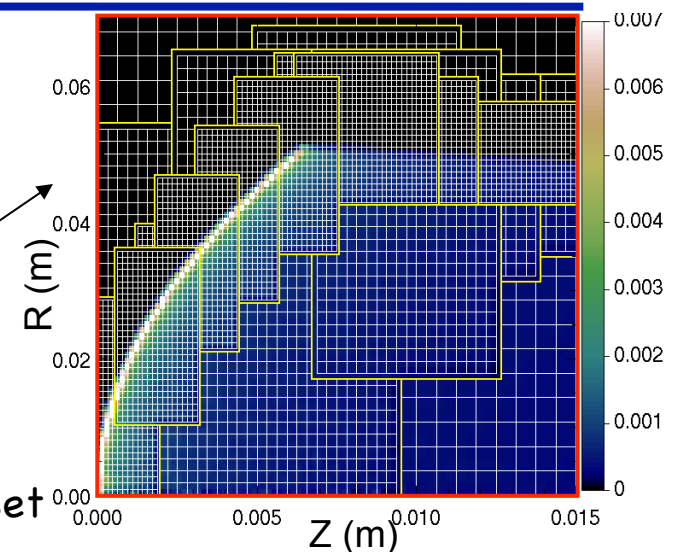
HCX beam line

Q1 (a) **Q2** (b) **Q3** (c) **Q4**
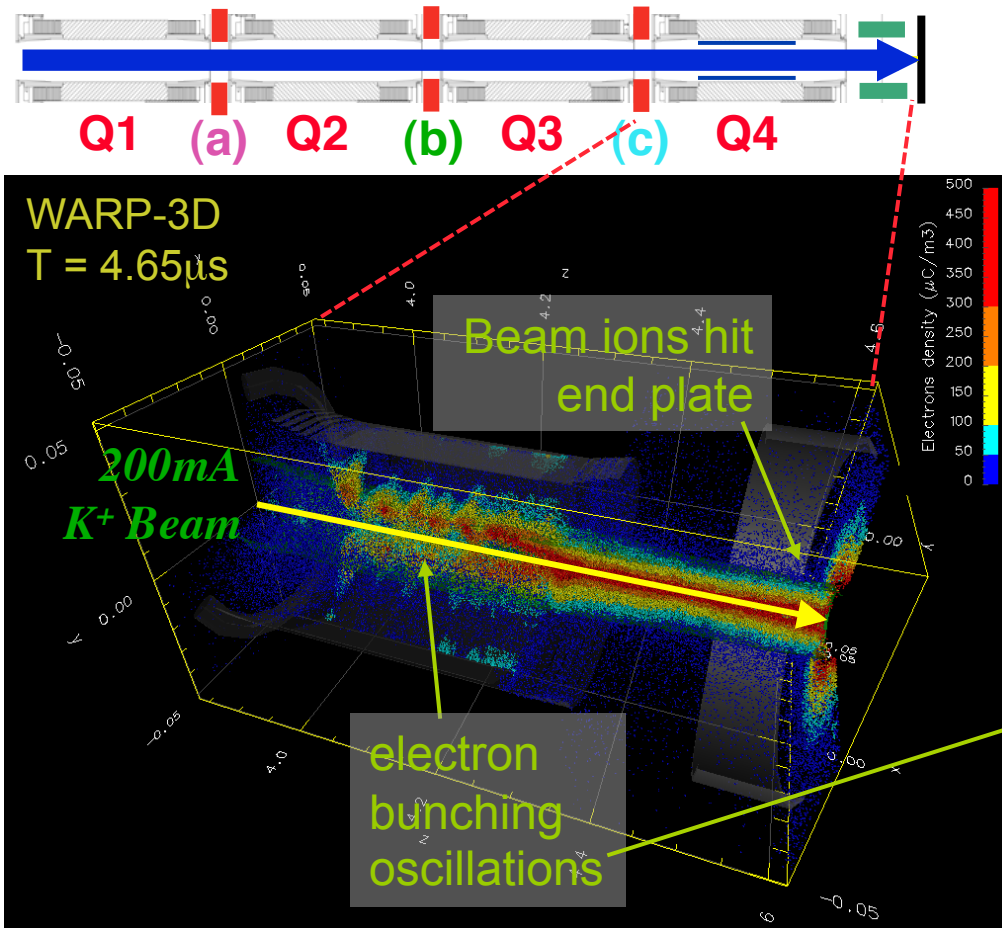
6-MHz oscillations were seen first in simulations; then they were sought and measured at station (c) in experiments.

WARP-3D
T = 4.65μs

Beam ions hit end plate

200mA K⁺ Beam

electron bunching oscillations

Electrons density (μC/m3)

Simulation
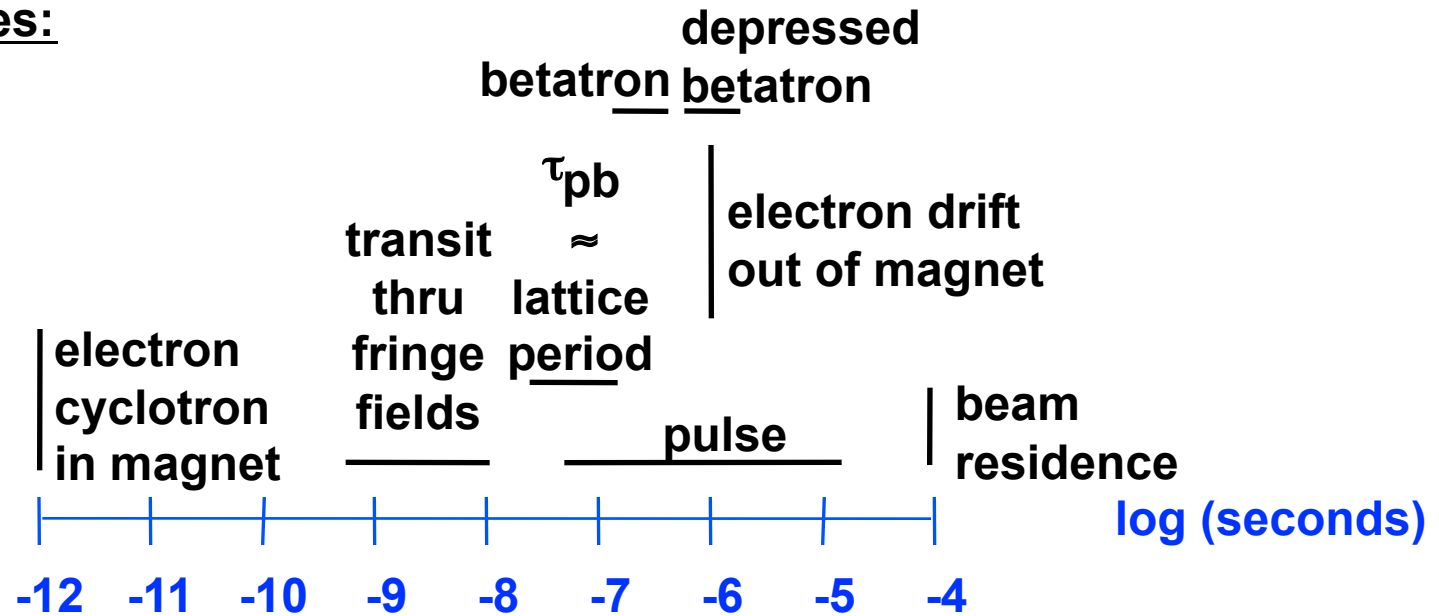Experiment

(c)

I (mA)

time (μs)

Warp: a parallel framework combining features of plasma (Particle-In-Cell) and accelerator codes

- **Geometry:** 3D (x,y,z), 2-1/2D (x,y), (x,z) or axisym. (r,z)

- **Python and Fortran:** "steerable," input decks are programs

- **Field solvers:** Electrostatic - FFT, multigrid; implicit; AMR
  Electromagnetic - Yee, Cole-Kark.; PML; AMR

- **Boundaries:** "cut-cell" --- no restriction to "Legos"

- **Applied fields:** magnets, electrodes, acceleration gaps, user-set

- **Bends:** "warped" coordinates; no "reference orbit"

- **Particle movers:** Energy- or momentum-conserving; Boris, large time step "drift-Lorentz", novel relativistic Leapfrog

- **Surface/volume physics:** secondary e⁻ & photo-e⁻ emission, gas emission/tracking/ionization, time-dependent space-charge-limited emission

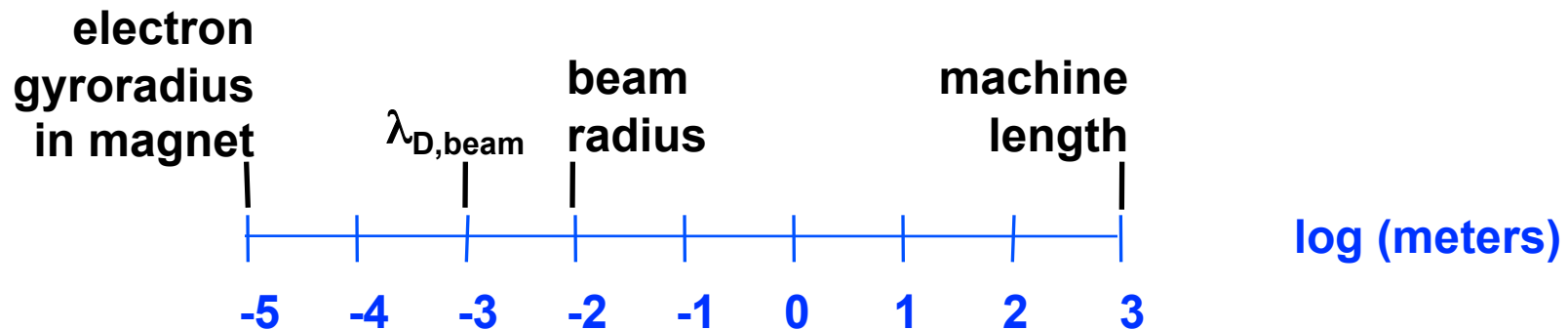- **Parallel:** MPI (1, 2 and 3D domain decomposition)

Warp 3D EM/PIC on Franklin

Warp 3D on Franklin
512x512x512 cells
8 particles/cell

32,768 cores

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Time and length scales span a wide range

Time scales:

depressed

betatron betatron

τ_{pb}

$\approx$

electron drift
out of magnet

transit
thru   lattice
fringe period
fields

electron
cyclotron
in magnet

pulse

beam
residence

log (seconds)

-12   -11   -10   -9   -8   -7   -6   -5   -4

Length scales:

electron
gyroradius
in magnet

$\lambda_{D,beam}$

beam
radius

machine
length

log (meters)

-5   -4   -3   -2   -1   0   1   2   3
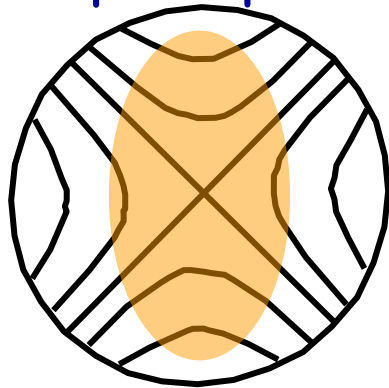
New "Drift-Lorentz" mover relaxes the problem of short electron timescales in magnetic field*

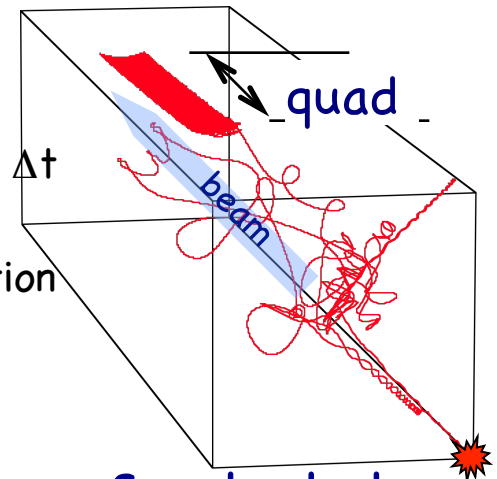## Magnetic quadrupole

Problem: Electron gyro timescale

    << other timescales of interest

$\Rightarrow$ brute-force integration <u>very</u> slow due to small Δt

Solution*: Interpolation between full-particle dynamics ("Boris mover") and drift kinetics (motion along B plus drifts)

$$\mathbf{v}_{eff} = \mathbf{b}(\mathbf{b} \cdot \mathbf{v}_L) + \alpha \mathbf{v}_{L,\perp} + (1-\alpha)\mathbf{v}_d$$
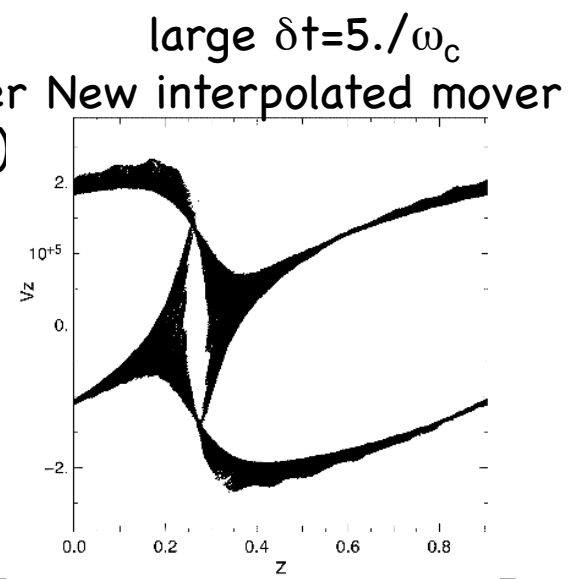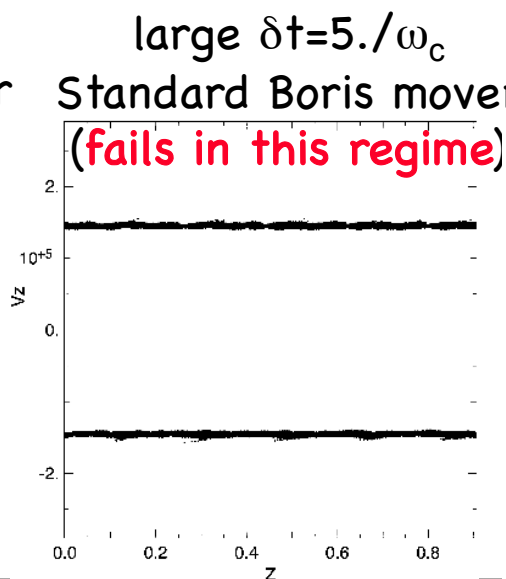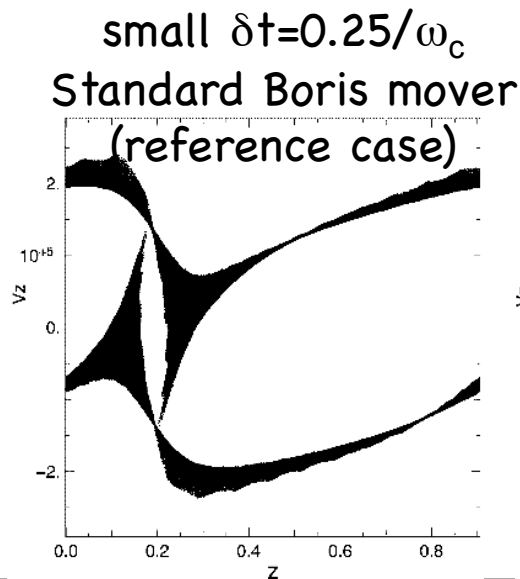
correct gyroradius with $\alpha = 1/[1+(\omega_c \delta t/2)^2]^{1/2}$

quad

beam

Sample electron motion in a quad

Test:

Magnetized two-stream instability

small $\delta t = 0.25/\omega_c$ Standard Boris mover (reference case)	large $\delta t = 5./\omega_c$ Standard Boris mover (fails in this regime)	large $\delta t = 5./\omega_c$ New interpolated mover

*R. Cohen et. al., *Phys. Plasmas*, May 2005

Electrostatic AMR simulation of ion source with the PIC code Warp: speedup x10

Run	Grid size	Nb particles
Low res.	56x640	~1M
Medium res.	112x1280	~4M
High res.	224x2560	~16M
Low res. + AMR	56x640	~1M

zoom

Refinement of gradients: emitting area, beam edge and front.